GEOTHERMAL HEAT PUMP SYSTEMS MODELING: TECHNICAL, ECONOMIC, AND ENVIRONMENTAL ANALYSIS FOR NATIONWIDE DEPLOYMENT IN COOLING-DOMINATED APPLICATIONS AND FOR SUSTAINABLE NEIGHBORHOOD DESIGN

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Multidisciplinary frameworks and tools are developed to assess the performance of geothermal heat pump (GHP) systems for heating and cooling applications in residential and commercial buildings. The technical, economic, and environmental performance (TEEP) of GHPs and traditional heating and cooling systems are explored for two applications: 1) cooling-dominated applications in cellular tower shelters nationwide; and 2) community-scale shallow geothermal (GHP) district energy (GSDE) systems for space heating and cooling.

Tens of thousands of cellular towers are in operation across the U.S. often accompanied by small shelters that house electrical equipment continuously generating around 8 kW_{th} of heat. The annual electricity consumption and corresponding carbon footprint for cooling shelters nationwide with conventional air-source heat pumps (ASHP) is significant. A systems engineering model (SEM) was developed to assess the TEEP of five cooling configurations for shelters located across various states with different climates and geologies. The five cooling configurations include: 1) GHP-only; 2) GHP + air-side economizer (AE); 3) GHP + dry-cooler (DC); 4) ASHP-only; and 5) ASHP + AE.

With no consideration of incentives or rebates, base case results show that the total cost of ownership (TCO) for all cooling configurations is the lowest for states located in cooler

climates (e.g., Maine, Minnesota, and Colorado), and the highest for states located in warmer climates (e.g., California, Florida). The configuration with the lowest TCO is ASHP + AE followed by GHP + AE. The configuration with the highest TCO is GHP-only, followed by GHP + DC and ASHP-only. Furthermore, the configuration with the lowest lifetime electricity consumption and CO_2e emissions is GHP + AE, and the highest is ASHP-only. With the use of energy-efficient GHP systems, regions with high electricity prices and consumption will experience lower costs and environmental impacts from a reduction in the operating conditions over the lifetime of the system (20 years).

Rust Belt cities in the U.S. have experienced years of severe economic and population decline, but possess many legacies and assets that present opportunities for sustainable revitalization and economic growth. Several frameworks and tools are proposed to assess the sustainable development potential of Utica, NY. Specifically, an integrative tool "GeoDistrict" is developed to assess the technical and economic performance of community-scale GSDE systems for space heating and cooling applications in downtown Utica.

In Utica, GSDE networks are economically feasible for systems designed to cover a portion of the annual peak heating load of the area, with the remainder load covered by a supplemental natural gas peak boiler. The capital costs and payback period for GSDE systems covering between 50 – 70% of the annual peak load of the area (2.7 – 6.0 MMBtu/hr) may range from \$1.0 million dollars – \$3.4 million dollars and 12 – 19 years, respectively. For system covering 100% of the annual peak load, the capital costs and payback period may be up to \$4.5 million dollars and over 21 years, respectively. Geothermal systems designed to cover a portion of the area's peak load may be economically viable and still provide for heating during a significant portion of the year.

BIOGRAPHICAL SKETCH

Gloria "Andrea" Aguirre was born in Monterrey, Mexico, but has lived in the U.S. since 1999. In the Fall 2008, Andrea finished an Associate of Applied Science in Geographic Information Systems (GIS) and an Associate of Science at Lone Star College in Houston, Texas. In the Spring 2010, Andrea obtained a B.S. in Environmental Engineering from Southern Methodist University (SMU) in Dallas, Texas.

While pursuing her B.S. degree, Andrea participated in a one-year undergraduate research experience at the SMU geothermal lab, and a two-year water resources internship with Nathan D. Maier Consulting Engineers, Inc. In 2010, Andrea participated in a summer internship with CDM Smith in Sacramento, California working in the area of water resources.

In the Summer 2014, Andrea obtained a M.S. from the Civil and Environmental Engineering department at Cornell University. Andrea's M.S. thesis focused on analyzing spatial variability and performing uncertainty analysis for a geothermal resource assessment study in the Appalachian Basin of New York and Pennsylvania.

During the Fall 2014, Andrea enrolled in the Ph.D. program in Geological Sciences at Cornell University working under the supervision of Professors Jefferson W. Tester, Teresa E. Jordan, and Albert R. George. Andrea's dissertation has focus on systems modeling of shallow geothermal heat pump systems for nationwide application in cooling cellular tower shelters and for sustainable neighborhood design.

While at Cornell, Andrea participated in several National Science Foundation programs, Diversity Programs in Engineering, and several student organizations. Andrea has held officer positions in the Society of Women Engineers-Graduate Branch (GradSWE), and has been a member of the President Sustainability Campus Executive Committee (PSCC) since 2016.

"Our population and our use of the finite resources of planet Earth are growing exponentially, along with our technical ability to change the environment for good or ill." – ***Stephen Hawking***

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NOMENCLATURE

List of Abbreviations

AC-DC	Alternative Current to Direct Current Power Systems
AE	Air-Side Economizer
AECS	Annual Energy Cost Savings
AFUE	Annual Fuel Use Efficiency
ASHP	Air-Source Heat Pumps
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
AZNM	Western Electric Coordinating Council - Southwest
BAU	Business-as-Usual
BHE	Borehole Heat Exchanger
BSU	Ball State University
CAMX	Western Electric Coordinating Council - California
CAP	Capital Costs
CC	Cooling Capacity
CCE	Cornell Cooperative Extension
CEO	Chief Executive Officer
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CNU	Congress for the New Urbanism
DC	Dry-Cooler
DOE	U.S. Department of Energy
DSIRE	Database of State Incentives for Renewables and Efficiency
EER	Energy Efficiency Ratio
eGRID	Emissions & Generation Resource Integrated Database

EGS	Enhanced Geothermal Systems
EIA	U.S. Energy Information Agency
EJ	Exajoule (1 EJ = 10^{18} Joules)
EPA	U.S. Environmental Protection Agency
ERCT	Electric Reliability Council of Texas
EWT_L	Load Entering Watering Temperature
EWT_s	Source Entering Water Temperature
ft	Feet (English Engineering Units)
FRCC	Florida Reliability Coordinating Council
GAO	U.S. General Accounting Office
GHG	Greenhouse Gas
GHP	Geothermal (Ground-Source) Heat Pumps
GIB	Green Infrastructure and Building
GIS	Geographic Information Systems
GPM	Gallons per Minute
GSDE	Geothermal (Ground-Source) District Energy
HC	Heating Capacity
HDD	Heating Degree Days
HDPE	High-Density Polyethylene
HE	Heat of Extraction of the Heat Pump
hr	Hour (Time)
HR	Heat of Rejection of the Heat Pump
HUD	U.S. Department of Housing and Urban Development
HVAC	Heating, Ventilation, and Air Conditioning
IDHA	International District Heating Association

IGSHPA	International Ground Source Heat Pump Association
kW	Kilowatt Energy
kWh_e	Kilowatt hour (Electric Energy)
kWh_{th}	Kilowatt hour (Thermal Energy)
LCC	Life Cycle Cost
LCO_2e	Lifetime CO_2-equivalent Emissions
LCOH	Levelized Cost of Heat
LEC	Lifetime Electricity Consumption
LEED-ND	Leadership in Energy and Environmental Design for Neighborhood Development
LOM	Lifetime Operating and Maintenance Costs
LWT_L	Load Leaving Water Temperature
LWT_s	Source Leaving Water Temperature
M	Thousand
MACRS	Modified Accelerated Cost Recovery System
MM	Million
MMBtu	Million British Thermal Units
MROE	Midwest Reliability Organization – East
MROW	Midwest Reliability Organization - West
MVCC	Mohawk Valley Community College
MW	Megawatt Energy
NERC	North American Electric Reliability Corporation
NEWE	Northeast Power Coordinating Council - New England
NO	Nitrogen Oxide
NPD	Neighborhood Pattern and Design
NRDC	Natural Resources Defense Council

NREL	National Renewable Energy Lab
NSRDB	National Solar Radiation Data Base
NWPP	Western Electric Coordinating Council - Northwest
NY	New York State
NYCW	Northeast Power Coordinating Council - NYC/Westchester
NYLI	Northeast Power Coordinating Council - Long Island
NYSERDA	New York State Energy Research and Development Authority
NYUP	Northeast Power Coordinating Council - Upstate New York
PB	Payback Period
PCA	Power Control Areas
PE	Polyethylene Casing Pipe
RFCE	Reliability First Corporation – East
RFCM	Reliability First Corporation – Michigan
RFCW	Reliability First Corporation – West
RMPA	Western Electric Coordinating Council – Rockies
ROI	Return on Investment
PUR	Polyurethane Insulation Foam
PV	Solar Photovoltaic
R2G	Rust to Green
SO_2	Sulfur Dioxide
SEER	Seasonal Energy Efficiency Ratio
SEM	Systems Engineering Model
SLL	Smart Growth and Linkage
SPNO	Southwest Power Pool – North
SPSO	Southwest Power Pool – South

SRMV	SERC Reliability Corporation - Mississippi Valley
SRMW	SERC Reliability Corporation – Midwest
SRSO	SERC Reliability Corporation – South
SRTV	SERC Reliability Corporation - Tennessee Valley
SRVC	SERC Reliability Corporation - Virginia/Carolina
TCO	Total Cost of Ownership
TEEP	Technical, Economic, and Environmental Performance
TMY	Typical Meteorological Year
TRNSYS	Transient System Simulation Program
TRT	Formation Thermal Response Test
U.S.	United States of America
USGBC	United States Green Building Council
W	Watt Energy
WRI	World Resource Institute
WSGHP	Water-Source Geothermal Heat Pumps

List of Symbols

$c_{p,DP}$	Specific heat capacity of the water in the distribution pipes (J/kg·K)
$C_{C,ASHP}$	Cooling cost rate for ASHPs ($/MMBtu)
$C_{C,WSGHP}$	Cooling cost rate of WSGHPs ($/MMBtu)
C_{cap}	Total capital investment cost for the energy production, distribution, and consumption systems ($MM) of the Geothermal District Energy Network
C_{DD}	Cooling load per degree day (Btu/DD)
$C_{H, fur}$	Heating cost rate for furnaces or boilers ($/MMBtu)
$C_{H,WSGHP}$	Heating cost rate of WSGHPs ($/MMBtu)

$C_{O\&M}$	Total lifetime (20 years) operation and maintenance costs for the energy production, distribution, and consumption system ($MM) of the Geothermal District Energy Network
CC_{HP}	Cooling capacity of the heat pump unit in cooling mode (Btu/hr)
CF_y	Cash flow in year y ($)
$COP_{cooling}$	Coefficient of performance during cooling operation (-)
COP_D	Coefficient of performance at design heating conditions (-)
$COP_{heating}$	Coefficient of performance during heating operation (-)
c_w	Heat capacity of water (J/kg·K)
dr	Discount rate (-)
D_B	Diameter of the geothermal bore (in.)
$D_{DP,i}$	Inside diameter of the distribution pipe (in.)
D_P	Diameter of the geothermal Nominal U-Bend pipe (in.)
EER_D	Energy efficiency ratio at design cooling conditions (-)
$EWT_{L,C}$	Load entering water temperature at design conditions in cooling mode (°F)
$EWT_{L,H}$	Load entering water temperature at design conditions in heating mode (°F)
$EWT_{S,C}$	Source entering water temperature at design conditions in cooling mode (°F)
$EWT_{S,H}$	Source entering water temperature at design conditions in heating mode (°F)
E_y	Energy (heat) generation in year y
g	Gravity constant (ft/s²)
GPM_L	Load flow rate of the heat pump (GPM)
GPM_S	Source flow rate of the heat pump (GPM)
f	Friction factor (-) for smooth pipes
F_H	Run fraction in heating mode (-)
$h_{f,DP}$	Head loss due to friction in the distribution pipes (ft.)
H_{DD}	Heating load per degree day (Btu/DD)

HC_D	Estimated heating capacity of the geothermal field at design conditions (Btu/hr)
HC_{HP}	Heat pump capacity at design conditions (Btu/hr)
HE_{HP}	Heat of extraction of the heat pump in heating mode (Btu/hr)
HR_{HP}	Heat of rejection of the heat pump to the ground connection in cooling mode (Btu/hr)
ir	Inflation rate (-)
K_{DP}	Thermal conductivity of the buried pre-insulated distribution pipe (W/m·K)
$K_{f,s}$	Thermal conductivity (effective) of the soil/rock formation (W/m·K)
K_G	Thermal conductivity of the ground (W/m·K)
K_{GROUT}	Thermal conductivity of the grout (W/m·K)
K_{PE}	Thermal conductivity of the PE pipe (W/m·K)
K_{PUR}	Thermal conductivity of the PUR insulation (W/m·K)
K_{sand}	Thermal conductivity of the sand backfill (W/m·K)
K_{soil}	Thermal conductivity of the soil backfill (W/m·K)
K_{steel}	Thermal conductivity of the steel pipe (W/m·K)
L	Typical borehole spacing (m)
lt	Expected lifetime of the system (20 years)
L_{DP}	Total pipeline distribution length (ft.)
$L_{H,T}$	Total borehole heating design length per geothermal field (ft.)
L_N	Length of the distribution pipe from the consumption node to the heat central location (m)
$LCOH$	Levelized cost of heat ($/MMBtu)
$LWT_{L,C}$	Load leaving water temperature at design conditions in cooling mode (°F)
$LWT_{L,H}$	Load leaving water temperature at design conditions in heating mode (°F)
$LWT_{S,C}$	Source leaving water temperature at design conditions in cooling mode (°F)
$LWT_{S,H}$	Source leaving water temperature at design conditions in heating mode (°F)

$\dot{m}$	Total mass flow rate per geothermal field (kg/s)
$\dot{m}_{DP}$	Mass flow rate in the distribution pipes (kg/s)
n	Porosity (-)
P_{pump}	Pumping power (W)
Pe	Péclet number (-)
q_{DP}	Heat loss per meter of buried pre-insulated distribution pipe (W/m)
Q_L	Total estimated heat load (Btu/hr)
$R_B + R_G \bullet F_H$	Vertical borehole ground loop resistance in heating mode (hr·ft·°F/Btu)
Re	Reynolds number (-)
r_{steel}	Radius of the steel pipe (m)
R_{PE}	Thermal resistance of the PE casing pipe (m·K/W)
R_{PUR}	Thermal resistance of the PUR insulation foam (m·K/W)
R_{sand}	Thermal resistance of the sand backfill (m·K/W)
R_{soil}	Thermal resistance of the soil backfill (m·K/W)
R_{steel}	Thermal resistance of the steel pipe (m·K/W)
$T_{avg,DHT}$	Average ground temperature of the district heating trench (°C)
$T_{avg,DHW}$	Average temperature of the district heating water (°C)
T_i	Indoor design temperature (°F)
T_o	Annual mean surface temperature (°C)
$T_{o,C}$	Outdoor cooling design temperature (°F)
$T_{o,H}$	Outdoor heating design temperature (°F)
$T_{r,DHW}$	Return district heating water temperature to heat central location (°C)
$T_{s,DHW}$	Supply district heating water temperature to consumption nodes (°C)
T_G	Average temperature of the ground (°F)
$T_{N,DHW}$	Temperature of the district heating water leaving each consumption node (°C)

TCO	Total cost of ownership ($MM)
$\dot{V}_{DP}$	Volumetric flow rate in the distribution pipe (GPM)
$\dot{V}_{HP}$	Volumetric flow rate of each heat pump unit (GPM)
$y_{C,DD}$	Annual cooling degree days (DD)
$y_{H,DD}$	Annual heating degree days (DD)
$y_{L,C}$	Yearly cooling load (MMBtu/year)
$y_{L,H}$	Yearly heating load (MMBtu/year)

List of Greek Symbols

γ_{DP}	Specific weight of the of fluid in the distribution pipe (N/m^3)
δ_{PE}	Thickness of the PE pipe (m)
δ_{PUR}	Thickness of the PUR insulation foam (m)
δ_{sand}	Thickness of the sand backfill (m)
δ_{soil}	Thickness of the soil backfill (m)
δ_{steel}	Thickness of the steel pipe (m)
$\Delta p_{,DP}$	Pressure loss in the distribution pipes (N/m^2 or Pa)
Δt	Temperature drop in the district heating pipes (°C)
η	Pump efficiency (%)
μ_{DP}	Fluid viscosity in the distribution pipe (cP)
v_D	Darcy velocity (m/day)
v_{DP}	Fluid flow velocity in the distribution pipe (ft/sec)
ρ_{fluid}	Density of heat exchanger fluid (kg/m^3)
$\rho_{fluid,DP}$	Density of fluid in the distribution pipe (lb/ft^3)
ρ_w	Density of water (kg/m^3)

List of Subscripts

avg	Average
ASHP	Air source heat pumps
B	Borehole
C	Cooling
cap	Capital Investment
D	Design conditions
DD	Degree Day
DP	Distribution Pipe
DHT	District heating trench
DHW	District heating water
e	Electric Energy
f	Friction
fur	Furnaces/Boilers
G	Ground
H	Heating
HP	Heat pump unit
i	Indoor/Inside
L	Load
min	Minimum
N	Consumption Node
o	Outdoor
O&M	Operation and Maintenance
P	Pipe
PE	Polyethylene casing pipe

PUR	Polyurethane insulation foam
r	Return district heating water
s	Supply district heating water
S	Source
steel	Steel pipe installed in the distribution network
T	Total
th	Thermal Energy
WSGHP	Water source geothermal heat pump
y	Year

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Chapter 4

Appendix A

Appendix B

Chapter 1: Introduction and Motivation

CHAPTER 1

INTRODUCTION AND MOTIVATION

This dissertation develops multidisciplinary frameworks and tools to assess the technical, economic, and environmental performance (TEEP) of geothermal (ground-source) heat pump (GHP) systems for space heating and cooling applications. In addition, this dissertation uses such frameworks and tools to provide case studies of GHP deployment nationwide for cooling cellular tower shelters and for sustainable neighborhood design.

In 2015, the primary energy consumption in the United States (U.S.) was around 97 quadrillion BTU (102 EJ; 1 EJ = 10^{18} J), roughly 18% of the world's total energy consumption (U.S. EIA, 2017a). About 40% of the U.S. primary energy consumption occurs in the residential and commercial sectors for space heating and cooling applications (U.S. EPA, 2016; U.S. EIA, 2017a; 2017b). Currently, space heating and cooling is provided by the combustion of fossil fuels at very high temperatures. Thermal energy may be supplied more sustainably by using lower grade renewable heating and cooling technologies, including direct use geothermal resources (Fox et al., 2011).

Geothermal energy is a viable renewable energy source with the potential to provide a vast amount of thermal energy originated and stored in the Earth. A wide range of geothermal systems, from shallow GHPs to Enhanced Geothermal Systems (EGS), can produce heat and/or power at competitive market costs depending upon the characteristics of the resource. Geothermal resource temperatures may range from under 30 °C to over 300 °C (86 – 572 °F) (Lund, 2007).

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In Figure 1.1, the utilization of geothermal energy at various temperatures is provided (Steingrímsson, 2013; UNU-GTP, 2018; adapted from Líndal, 1973). Temperatures above 150 °C may be used for electric power generation by using geothermal power plant technologies that include binary cycles, dry steam, and flash steam systems. Binary cycles generally represent resource temperatures below 180 °C, whereas steam systems resource temperatures may exceed 220 °C. Temperatures below 150 °C are typically used for direct-use geothermal heating and cooling applications. Temperatures in the range of 5 °C to 30 °C may be used with GHP systems for space heating, cooling, and domestic hot water generation (Lund, 2007).

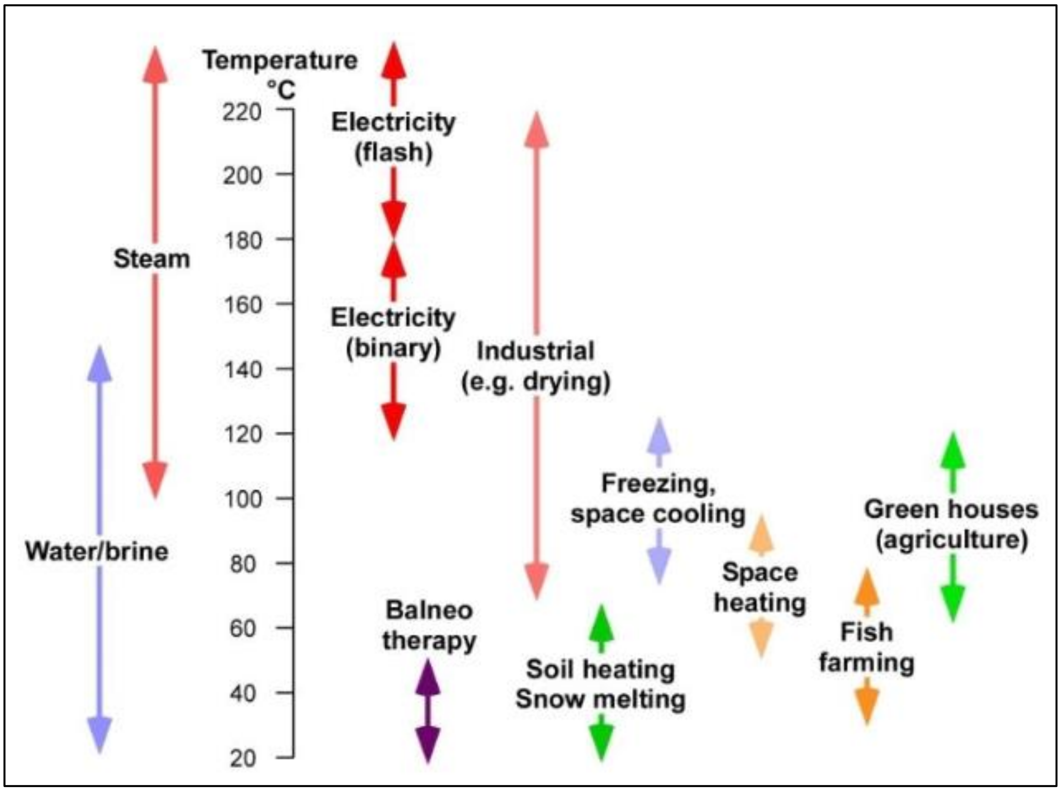

Figure 1.1 – Geothermal energy utilization temperatures (Steingrímsson, 2013; UNU-GTP; 2018; adapted from Líndal, 1973).

The utilization of direct-use geothermal resources worldwide includes space heating and cooling, bathing, greenhouses, aquaculture, and industrial applications, among others. In Figure 1.2, a comparison of the worldwide utilization of direct-use geothermal energy applications is provided. The largest distribution of direct-use geothermal energy is for space heating and cooling with GHP systems (~ 55%), bathing and swimming (~ 20%), and space heating from district heating systems (~15%) (Lund and Boyd, 2015).

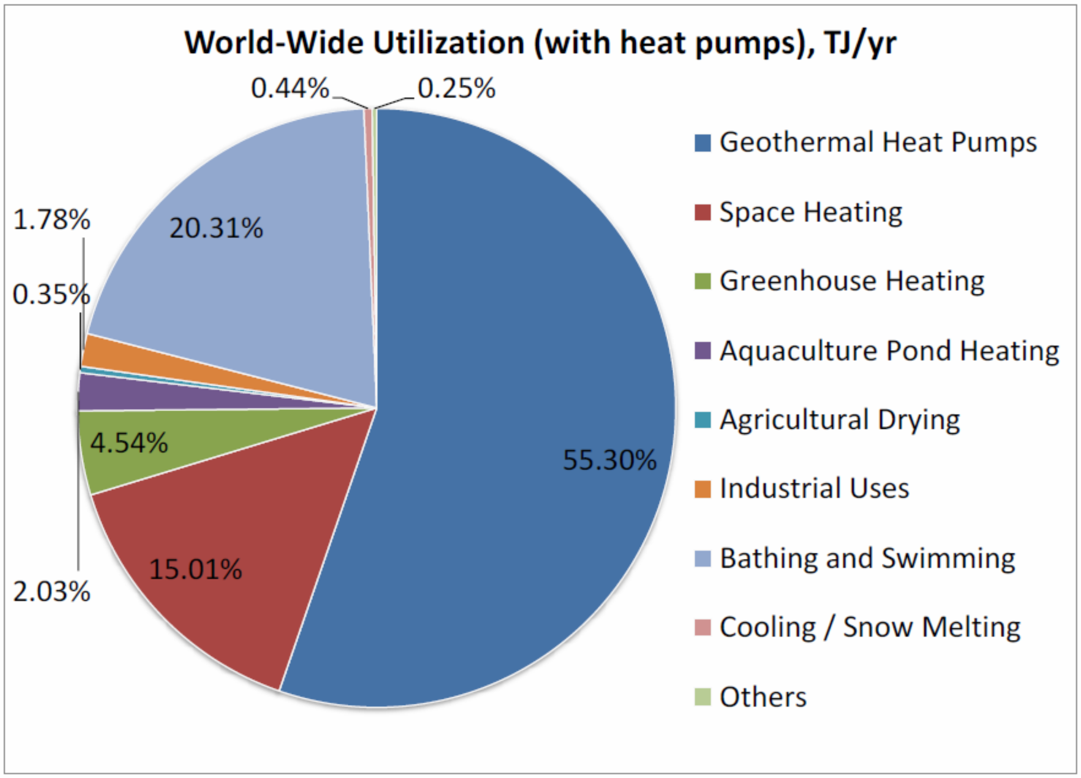

Figure 1.2 – Distribution of direct-use geothermal energy utilization worldwide (Lund and Boyd, 2015).

GHP systems have increased in popularity because these systems can efficiently provide for space heating and cooling everywhere in the world regardless of the local geothermal resource. GHPs utilize the heat of the earth as a heat source during the winter and heat sink during the summer. At shallow depths (less than 150 m or 500 ft.), the Earth maintains a relatively constant temperature of around 10 – 13 °C (50 – 55 °F) making the use of GHP systems feasible year round (Glassley, 2010; Tester et al., 2012).

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GHPs are more efficient than traditional heating and cooling systems because the ground experiences less temperature variations than ambient air temperatures. Even in the coldest nights, GHPs can reach efficiencies of 300 – 600%, and can reduce heating and cooling energy by as much as 40% and 50%, respectively, compared to traditional heating and cooling systems (Philappacopoulos and Berndt, 2001; Omer, 2008; U.S. DOE, 2011). In addition to high system performance efficiencies, benefits of GHPs include low lifetime maintenance and operating costs, less mechanical room space requirements, and lower greenhouse gas (GHG) emissions than traditional heating and cooling systems.

The U.S. is a world leader in the installation of GHP systems. Currently, over 1.4 million units are in operation, and the annual installation growth rate is around 8%. GHP systems in the U.S. account for over 85% of the direct-use geothermal resources (Lund and Boyd, 2015). However, GHP installations in the U.S. account for less than 2% of the overall heating, ventilating, and air conditioning (HVAC) industry (Battocletti and Glassley, 2010; GEO, 2015).

Factors affecting market penetration of GHPs include high installation costs, consumers' and policymakers' lack of awareness and/or distrust in the system benefits, and lack of experienced designers and installers, among others. The high installation cost of the ground loop system is considered as the primary barrier to a wider adoption of GHPs. However, financial incentives at the local, state, and federal level can make installation of GHP systems more feasible to residential and commercial owners (Hughes, 2008; Liu et al., 2012).

In this dissertation, multidisciplinary frameworks and tools are developed to increase awareness of the benefits and costs of installing GHP systems nationwide. The frameworks and tools assess the TEEP of GHP systems with consideration of variations in costs, climate, geology, and environmental emissions. The TEEP of GHPs and traditional heating and cooling systems are explored for two applications: 1) cooling-dominated applications in cellular tower shelters nationwide; and 2) community-scale shallow geothermal (GHP) district energy systems for space heating and cooling.

Tens of thousands of cellular tower shelters are in operation across the U.S. Most of the towers are accompanied by small shelters that house electrical equipment continuously generating around 8 kW_{th} of heat. The annual electricity bill for cooling the shelters with conventional air-source heat pump (ASHP) systems and their corresponding carbon footprint is significant. The overall project objectives compare the TEEP of various GHP configurations to determine if these systems are a more economical and reliable choice over ASHPs for cooling-dominated applications. The TEEP methodology for cooling of cellular tower shelters was developed in collaboration with Verizon Wireless and graduate students at Cornell University (Beckers, 2016; Aguirre et al., 2017).

Rust Belt cities in the U.S. have experienced years of severe economic and population decline, but possess many legacies and assets that present opportunities for sustainable revitalization and economic growth. The overall project objectives involve the development of frameworks and tools to assess the sustainable development potential of Utica, NY. Specifically, opportunities to retrofit buildings, integrate solar and geothermal energy in the community, and redesign the urban fabric of Utica are explored. Community-scale shallow GHP district energy systems are proposed for space heating and cooling applications in downtown Utica. The analysis of sustainable development potential to transform Utica's urban core was developed in collaboration with faculty and students from various departments at Cornell University (George et al., 2016).

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CHAPTER 2

DISSERTATION OBJECTIVES, APPROACH, AND ORGANIZATION

2.1: Objectives

The dissertation has two major objectives. The first objective is to assess the technical, economic, and environmental performance (TEEP) of hybrid geothermal heat pump (GHP) and air-source heat pump (ASHP) systems for cooling of cellular tower shelters nationwide. The second objective is to develop an integrative framework and tool to assess the technical and economic performance of shallow geothermal (GHP) district energy systems (GSDE) at a neighborhood scale.

2.2: Approach

For the first objective, the approach was to develop a systems engineering model (SEM) to assess the TEEP of five cooling configurations nationwide. The SEM consists of a multidisciplinary framework that characterizes the U.S. with consideration of various climatic and hydrogeological regions, estimated population and cell tower densities, capital expenditure and operating costs, and environmental emissions. The five cooling configurations consider GHP in combination with air-side economizers (AE) and dry-coolers (DC), and ASHP in combination with AE systems. A sensitivity analysis of technical and financial parameters is provided to assess the variability in the TEEP of the cooling configurations.

For the second objective, the approach was to develop the “GeoDistrict” tool by using a Microsoft Excel interface intended for users with minimal to no experience in GSDE systems design. The GeoDistrict tool contains six tabs, and applies design and installation principles of

GHP and district energy networks. The design and installation principles include primary equations, variables, and assumptions to provide a first-order approximation of the technical and economic feasibility of installing GSDE systems in small-to-mid-size communities for space heating and cooling applications. The tool adapts to various geographic and geologic regions by modifying the assumptions in the model.

The first objective includes methodology developed in collaboration with Verizon Wireless and graduate students at Cornell University. The group includes Jim Feeney from Verizon Wireless, and Dr. Koenraad Beckers, Dr. Maciej Lukawski, and Professor Jefferson W. Tester from the Cornell Energy Institute. Preliminary findings of the SEM for cooling cellular tower shelters nationwide are summarized in a paper presented at the Forty-Second Workshop on Geothermal Reservoir Engineering in Stanford University (Aguirre et al., 2017). Furthermore, the work presented in chapters 3 and 4 builds from a proof-of-concept study by LaBrozzi et al. (2010) on cooling of cellular tower shelters nationwide, and the Cornell-Verizon hybrid GHP experimental and modeling work presented by Beckers (2016).

The second objective includes methodology developed in collaboration with faculty, undergraduate, and graduate students at Cornell from different departments, including Engineering and Landscape Architecture. The group includes the following professors: Albert R. George, Paula H. Horrigan, Norman R. Scott, and Jefferson W. Tester. The undergraduate and graduate students include Tianshu Li, Angela Moreno-Long, Pradeep Prathibha, Sivan Sud, David Torrey de Frescheville, and Shanshan Cao. The work presented in chapters 5 and 6 builds from the report by George et al. (2016) on Sustainable Development Potential in Utica's Urban Core.

2.3: Organization

The dissertation is divided into two parts and has four major sections corresponding to seven chapters. Part I introduces GHP systems and their utilization potential for cooling-dominated applications nationwide. Part II introduces the GSDE framework and tool for sustainable development in small-to-mid-size communities.

The four major sections are divided into Chapters 1 and 2; Chapters 3 and 4; Chapters 5 and 6; and Chapter 7. Chapters 1 and 2 provide an introduction to the dissertation and the analysis. Chapter 3 introduces GHP systems for cooling-dominated applications. Chapter 4 presents the SEM developed to assess the TEEP of hybrid GHP and ASHP systems. In addition, Chapter 4 provides case studies and a sensitivity analysis of the TEEP for five cooling configurations nationwide.

Chapter 5 introduces GSDE systems for sustainable neighborhood development. Chapter 6 presents an integrative framework and tool for the assessment of GSDE in small-to-mid-size communities. Several case studies are provided in Chapter 6 summarizing the opportunities of GSDE implementation in a neighborhood within the Rust Belt City of Utica, NY. Chapter 7 provides the conclusions of the dissertation, and recommendations for future work.

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PART I:

INTRODUCTION TO GEOTHERMAL HEAT PUMP SYSTEMS AND THEIR UTILIZATION POTENTIAL FOR COOLING-DOMINATED APPLICATIONS NATIONWIDE

CHAPTER 3

GEOTHERMAL HEAT PUMP SYSTEMS FOR COOLING-DOMINATED APPLICATIONS

3.1: Introduction to Geothermal Heat Pump (GHP) Systems

Geothermal or ground-source heat pumps (GHP) utilize the heat of the earth at relatively shallow depths (less than 150 m or 500 ft.) to provide for space heating, cooling, and domestic hot water. At shallow depths, the Earth maintains a relatively constant temperature of around 10 – 13 °C (50 – 55 °F) throughout the year. The Earth's year-round constant temperature allows the ground to become a heat source in the winter and a heat sink in the summer (Glassley, 2010; Tester et al., 2012).

GHP systems are more efficient than traditional heating and cooling systems because the ground experiences less temperature variations than ambient air temperatures. Even in the coldest nights, GHPs can reach efficiencies of 300 – 600%, and are expected to consume approximately 25 – 50% less energy than air-source heat pumps (ASHP) (U.S. DOE, 2011). GHPs operate in a similar manner to ASHPs by transferring heat rather than generating it. However, GHPs transfer heat to the ground, whereas ASHPs transfer heat to the outside air (Omer, 2008).

The GHP system includes three major components: 1) Ground loop or borehole heat exchanger (BHE) connection; 2) Heat pump system; and 3) Air distribution system. The ground loop connection may be open or closed systems. An open system uses the groundwater directly as a heat carrier without any barriers between the rocks, soils, groundwater, and heat pump system (Omer, 2008). A closed system may include horizontal or vertical loops located underground. The ground loop (BHE) connection of closed systems consist of a set of high-density polyethylene (HDPE) pipes where a fluid circulating through the pipes exchanges heat with the surrounding ground in a closed loop. The circulating fluid may be a combination of water and antifreeze refrigerant mixture (Omer, 2008; IGSHPA, 2009).

In Figure 3.1, a schematic of the GHP system shows a closed ground loop vertical system and a heat pump system operating in cooling mode (Beckers, 2016). For both GHPs and ASHPs, the heat pump system is based on the vapor-compression and vapor-absorption cycle, and includes a compressor, condenser coil, expansion valve, and evaporation coil in a closed loop.

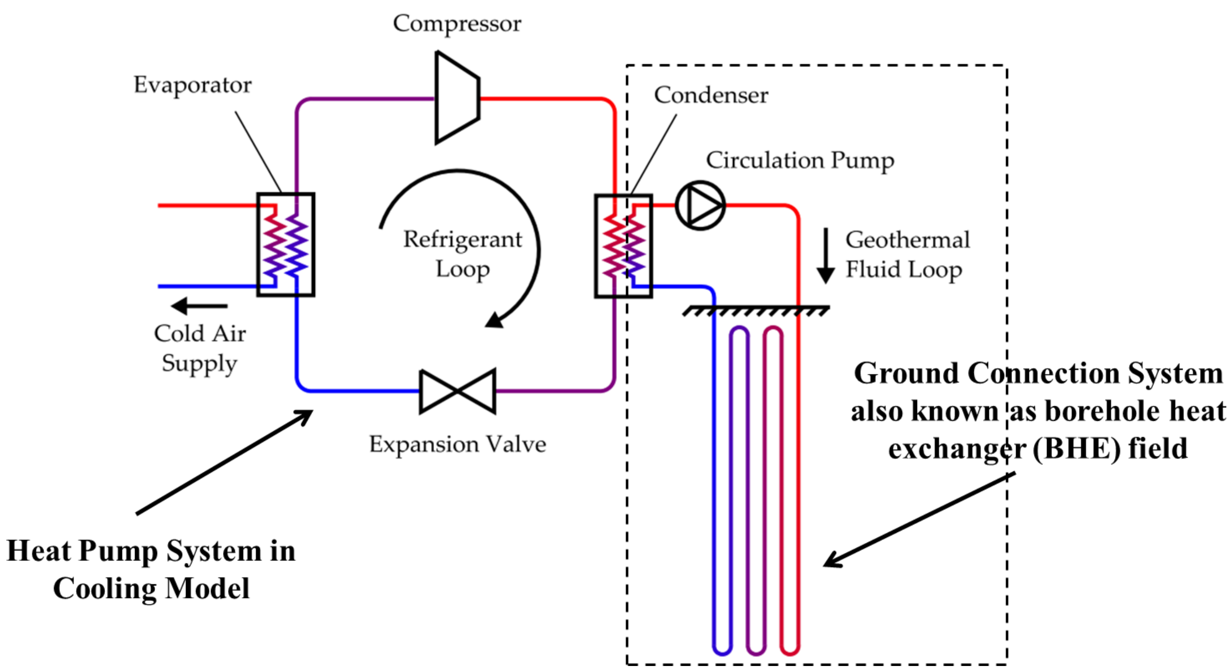

Figure 3.1 - Schematic of the geothermal heat pump system in cooling mode (adapted from Beckers, 2016).

During cooling mode, the condenser coil is coupled to the ground connection system where hot refrigerant vapor exchanges heat with the ground condensing into a cooler refrigerant liquid. The cooler refrigerant circulates through the expansion valve where the pressure of the refrigerant decreases, resulting in a temperature drop. The refrigerant circulates through the evaporator, coupled to a building's air distribution system, where cold air is supplied to a building and heat is absorbed. The warm refrigerant circulates through the compressor where the pressure and temperature of the fluid increases. The hot refrigerant vapor is then recirculated through the condenser coil, and the heat pump cycle continues (Staffell et al., 2012; Beckers, 2016).

During heating mode, the evaporator coil is coupled to the ground connection system and the condenser coil to a building's air distribution system (Beckers, 2016). The air distribution system includes conventional heating, ventilation, and air conditioning (HVAC) ductwork to distribute the heated or cooled air to the building (Omer, 2008; IGSHPA, 2009).

The heating and cooling efficiencies of heat pumps are expressed by the coefficient of performance (COP) defined as heat energy delivered to a building divided by the compressor electrical demand (IGSHPA, 2009; Glassley, 2010).

For heating and cooling operations, the COP of heat pumps is defined as:

$$\mathrm{COP}_{heating} = \frac{q_{heating}}{W} \tag{3.1}$$

$$\mathrm{COP}_{cooling} = \frac{q_{cooling}}{W} \tag{3.2}$$

with $COP_{heating}$ or $COP_{cooling}$ = coefficient of performance in heating or cooling mode (-), $q_{heating}$ or $q_{cooling}$ = heat energy delivered to buildings for space heating or cooling (W or kW), and W = compressor electrical demand (kW). For one unit of electricity input, GHP systems provide three to six units or more of heat output. ASHPs may deliver one-and-a-half to three units of heat output per electricity input (U.S. DOE, 2011).

Chapter 3: Geothermal Heat Pump Systems for Cooling-Dominated Applications

In addition to high system performance efficiencies, benefits of GHPs include low lifetime maintenance and operating costs, less mechanical room space requirements, and lower greenhouse gas (GHG) emissions than conventional ASHPs or air conditioning systems. Compared to conventional heating and cooling systems, GHPs can reduce maintenance costs by 50%, operating cost by 25%, and GHG emissions by over 65% (Omer, 2008).

GHPs can result more cost-effective than conventional ASHPs in regions characterized by high electricity prices, climates with high daily temperature variations, and in new building constructions. Because ASHPs use the outside air as a heat source or sink, their efficiencies significantly decrease under high temperature variations. As a result, ASHPs have been mostly installed in regions with moderate climates, including Southern and Western U.S. (Goetzler et al., 2009).

Approximately two-thirds of the global GHP installed capacity exists in the U.S., mostly in residential and commercial applications (Curtis et al., 2005; Goetzler et al., 2009). However, GHP installations in the U.S. account for less than 2% of the HVAC industry (Battocletti and Glassley, 2010; GEO, 2015). Historically, barriers to increased market penetration of GHP systems include lack of awareness and/or distrust in the system benefits, lack of experienced designers and installers, high capital costs, and uncertain return on investment (ROI). Even though GHP systems have longer expected lifetimes (over 20 years) and incur lower maintenance and operating costs compared to ASHPs (expected lifetime of 10 years), the biggest barrier to faster ROIs is the capital costs from ground loop drilling operations (Lienau et al., 1995).

3.2: Utilization Potential of Hybrid GHP Systems for Cooling-Dominated Applications Nationwide

To improve the economics of GHP installations, systems coupled with supplemental heat rejection units in cooling-dominated applications or supplemental heaters in heating-dominated applications have been proposed. In cooling-dominated applications, GHP systems may experience thermal imbalance in the BHE field over their lifetime due to continuous heat rejection to the ground. GHP systems coupled with air-cooled condensers, cooling towers, air-side economizers (AE), or dry-coolers (DC) may prevent heat accumulation in the ground, and reduce the BHE field size and operating costs (Hackel et al., 2008; Goetzler et al., 2009; Beckers, 2016).

In 2008, Hackel et al. compared the costs for cooling-dominated hybrid GHPs (in combination with cooling towers and DCs) for buildings of various sizes located across different climatic regions in the U.S. In regions with moderate and warm climates (e.g., Georgia), the life cycle cost (LCC) of hybrid GHPs is lower than GHP-only systems. For cool climates (e.g., Minnesota) with low cooling loads, the LCC is lower for GHP-only systems than for hybrid GHPs. Furthermore, the LCC for warm dry climates (e.g. Arizona) is roughly equivalent for hybrid GHPs and cooling tower-only systems (Hackel et al., 2008).

Beckers (2016) presented several hybrid GHP configurations for cooling-dominated applications in cellular tower shelters. The hybrid GHP configurations explored by Beckers (2016) include GHPs coupled with AE and DC units. From Figure 3.2, an AE allows cold outside air into a building and enables the GHP system to thermally recover as no heat rejection from the shelter into the ground occurs when the AE is in operation. From Figure 3.3, a DC is coupled with the BHE field and allows for active cooling of the reservoir ("recharging") during cold days (Beckers, 2016).

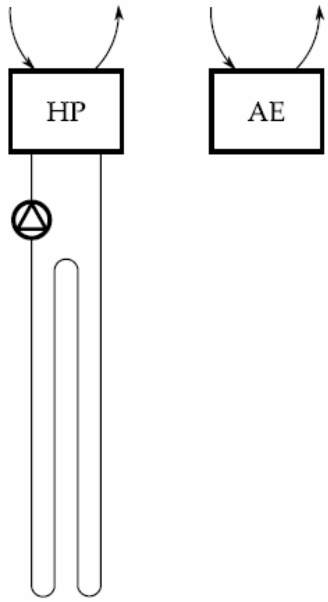

Figure 3.2 – Geothermal heat pump (GHP) system with air-side economizer (AE) (Beckers, 2016).

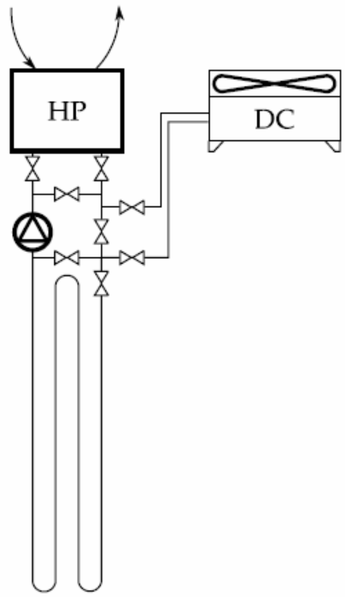

Figure 3.3 – Geothermal heat pump (GHP) system with dry-cooler (DC) (Beckers, 2016).

In Chapter 4, a system engineering model (SEM) is presented to assess the technical, economic, and environmental performance (TEEP) of hybrid GHP and ASHP systems for cooling of cellular tower shelters nationwide. The SEM for cooling of cellular tower shelters was first introduced at the Forty-Second Workshop on Geothermal Reservoir Engineering in Stanford University (Aguirre et al., 2017). Furthermore, the work presented in Chapter 4 builds from a proof-of-concept study by LaBrozzi et al. (2010) on cooling of cellular tower shelters nationwide, and the Cornell-Verizon hybrid GHP experimental and modeling work presented by Beckers (2016).

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CHAPTER 4

HYBRID GEOTHERMAL HEAT PUMPS FOR COOLING CELLULAR TOWER SHELTERS: FROM CAMPUS LIVING LABORATORY TO NATIONWIDE DEPLOYMENT

4.1: Introduction

The objectives of this chapter are to introduce a systems engineering model (SEM) to assess the technical, economic, and environmental performance (TEEP) of hybrid geothermal heat pump (GHP) and air-source heat pump (ASHP) systems for cooling of cellular tower shelters nationwide. Case studies summarizing the TEEP of five cooling configurations for shelters located across various states are discussed. In addition, a sensitivity analysis considering variations in technical and financial parameters is provided to assess the variability in the TEEP of the cooling configurations.

Tens of thousands of cellular tower stations are in operation across the U.S. Many cellular towers are accompanied by small shelters that house electronics, batteries, cabling, and alternating current to direct current (AC-DC) power systems used by telecommunication companies to transmit and process radio signals. The shelters protect the telecommunications equipment against severe weather conditions and/or vandalism (Beckers, 2016).

It is estimated that cellular tower shelters consume over 10 kW of electricity to transmit and process around 120 W of radio signals to and from cell phone subscribers. From the 10 kW of electricity consumed in the shelters, around 62% of the electricity is consumed by the electronics, 25% is consumed by the cooling equipment(s), and 11% is consumed by the AC-DC power systems. The remainder 2% is consumed by the load and feeder cable at the base of the tower (Roy, 2008). The electrical equipment in the shelters continuously (24/7) generate around

8 – 11 kW_{th} of internal heat. The annual operating and maintenance costs required for cooling these shelters with conventional ASHP systems and their corresponding carbon footprint are significant (Beckers, 2016; Aguirre et al., 2017).

In recent years, telecommunication companies have implemented energy efficiency and sustainability programs to reduce their carbon footprint and decrease energy costs. In 2009, the Chief Executive Officer (CEO) of Verizon Communications, Lowell McAdam, pledged to reduce Verizon's carbon footprint by 50% by 2020 from 2009 levels. Currently, Verizon is one of the two largest American telecommunications companies and the largest wireless telecommunications provider in the U.S. (Merchant, 2012; Verizon, 2018).

To achieve their long-term sustainability goals, Verizon committed to implementing 20 MW of green energy from solar photovoltaics (PV) and fuel cells, increasing water savings in data center operations, and installing energy-efficient technologies in cellular tower shelters and data centers. By the first quarter of 2016, Verizon reported a 54% reduction in their carbon footprint from 2009 levels from implementation of their energy efficiency and sustainability programs (Verizon, 2013a; 2013b; 2018).

In 2010, Verizon Wireless committed to a multiphase project in collaboration with Cornell University to investigate the TEEP of cooling cellular tower shelters with energy-efficient technologies. Phase 1 of the project involved a proof-of-concept study conducted by LaBrozzi et al. (2010) which showed that GHP systems in combination with air-side economizers (AE) present a cost-effective and energy-efficient alternative to conventional ASHP systems. LaBrozzi et al. (2010) assessed the overall life cycle cost (LCC) of GHPs and ASHPs by applying commercially available software, including GLHEPRO (IGSHPA, 2007) and GLD2009 (GaiaGeothermal, 2009).

In Phase 2, a full-scale and fully-monitored hybrid GHP system was designed and built at a Verizon Wireless cellular tower shelter in the Cornell University Plantations (Botanical Gardens) in Varna, NY. The design process began in the Fall 2011, and construction started in the Spring 2013. By the beginning of 2014, all systems began normal operation. The demonstration system has 6 boreholes (with almost 560 m of total borehole depth), and has been operating reliably and efficiently since installation (Beckers, 2016).

Phase 3 of the project involved modeling and validation of the hybrid GHP system in Varna, and analysis of the potential of GHPs for cooling shelters nationwide. The objectives of phase 3 were fourfold: 1) monitor and analyze the performance of the hybrid GHP system at the Varna site; 2) develop computer models and validate the models using data from the Varna site and from literature; 3) using the validated computer models, optimize the GHP system configuration, geometry of borehole heat exchangers (BHE), borehole field layout, and operating strategy; and 4) investigate the TEEP of cellular tower shelters equipped with hybrid GHP and ASHP systems at a nationwide scale (Beckers et al., 2016).

In the Spring of 2016, thermodynamic and heat transfer models of hybrid GHP and ASHP systems were developed by Beckers (2016) using the transient energy simulation software TRNSYS (Klein et al., 2010) to investigate and optimize system configuration for different operating conditions. Design and validation of the simulation models were summarized in Beckers (2016) using data collected both at the Varna site and from literature sources. The validated models became a major component in the development of a systems engineering model (SEM) to analyze the TEEP of hybrid GHP and ASHP systems for cooling of cellular tower shelters nationwide. The SEM characterized the nation with consideration of various climatic and hydrogeological regions, estimated population and cell tower densities, capital expenditure and operating costs, and environmental emissions.

The work presented in this chapter builds from the proof-of-concept study by LaBrozzi et al. (2010) described in phase 1, and the Cornell-Verizon hybrid GHP project presented by Beckers (2016) in phase 2 and phase 3 objectives 1 – 3. Specifically, this chapter covers a brief discussion of the methodology and results for objectives 1 – 3 of phase 3 in Section 4.2.7, but primarily focuses on methodology and results for objective 4 of phase 3.

In Section 4.2, an introduction to the SEM is provided including data collection and modeling of the six subsystems: national weather; tower placement; hydrogeology; cost; environmental emissions; and technical modeling. Section 4.3 evaluates and compares the TEEP of five cooling configurations across various states. Section 4.4 provides a sensitivity analysis considering variations in technical and financial parameters to assess the variability in the TEEP of the five cooling configurations. Finally, Section 4.5 provides conclusions and recommendations for cooling-dominated applications of hybrid GHPs nationwide.

4.2: Regional Geothermal Heat Pump (GHP) Systems Engineering Model (SEM)

The work presented in this section describes the development of the SEM applied nationwide to assess the TEEP of hybrid GHP and ASHP systems for cooling of cellular tower shelters. The objectives are to develop a multidisciplinary framework that characterizes the U.S. with consideration of various climatic and hydrogeological regions, estimated population and cell tower densities, capital expenditure and operating costs, and environmental emissions to compare the TEEP of five cooling configurations nationwide. The cooling configurations consider GHP in combination with air-side economizers (AE) or dry-coolers (DC), and ASHP in combination with AE systems.

Section 4.2.1 describes the SEM architecture, and provides an overview of the subsystems used to characterize the nation. Section 4.2.2 considers using meteorological databases to characterize the U.S. regional climate into "typical" meteorological years. Section 4.2.3 provides an estimate of the location of cellular tower shelters suitable for GHP retrofitting based on primary roads and population densities.

Section 4.2.4 describes hydrogeological regions across the nation and provides estimates of the thermal properties of rocks and soils within each region. Section 4.2.5 incorporates market analysis of the capital expenditure for GHP installations, electricity price variations by geographic regions, and available financial incentives for energy-efficient technologies. Section 4.2.6 provides estimates of the environmental emissions from electricity purchases to power shelters by Environmental Protection Agency (EPA) subregions. Section 4.2.7 discusses the technical subsystem component that incorporates experimental and modeling results from the Varna site summarized in Beckers (2016).

4.2.1: SEM Architecture and Subsystems Overview

To enable nationwide comparison of the TEEP for various cooling configurations in cellular tower shelters, a SEM that incorporates spatial, technical, and economic modeling was developed. The SEM architecture uses ArcGIS (ESRI, 2011) for spatial analyses, and models developed in TRNSYS (Klein et al., 2010) and MATLAB (MathWorks, 2009) software for technical and economic analyses.

Geographic information systems (GIS) are frequently used in the telecommunications industry to organize, manage, and analyze large volumes of data that enable planning for infrastructure improvements and/or network expansions (Tegou et al., 2007). With tens of thousands of cellular towers operating across the U.S., the development and improvement of telecommunications infrastructure often involves a complex interaction of spatial analyses to understand topographic restrictions, coverage patterns, and accommodate future growth (Cai, 2002; Scheibe et al., 2006).

From Figure 4.1, the regional GHP SEM spatial analyses involved nationwide data collection, managing, and modeling of five subsystems: 1) weather; 2) tower placement; 3) hydrogeological characterization; 4) costs; and 5) environmental emissions. With the nation characterized according to the five subsystems aforementioned, technical and economic models were applied to different geographic regions by incorporating experimental results and modeling efforts on hybrid GHP and ASHP systems for cooling shelters (Beckers, 2016). The SEM output compared the total cost of ownership (TCO), lifetime (20 years) electricity consumption (LEC), and lifetime CO_2-equivalent emissions (LCO_2e) for five cooling configurations: 1) GHP-only; 2) GHP + AE; 3) GHP + DC; 4) ASHP-only; and 5) ASHP + AE.

Chapter 4: Hybrid Geothermal Heat Pumps for Cooling Cellular Tower Shelters

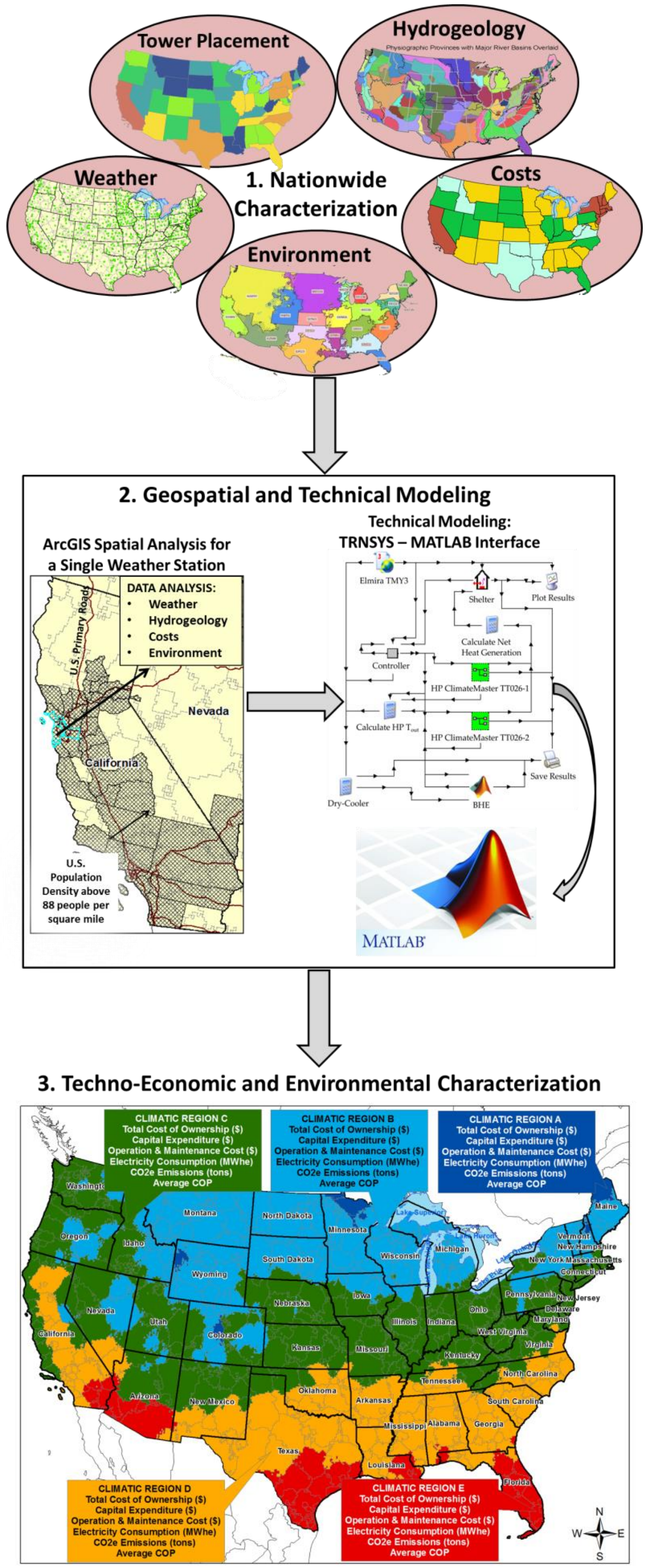

Figure 4.1 - Schematic of the regional geothermal heat pump (GHP) systems engineering model (SEM) for technical, economic, and environmental analyses of five cooling configurations in cellular tower shelters nationwide.

The weather subsystem uses U.S. climatic zones data normalized to a Typical Meteorological Year (TMY3). The TMY3 dataset contains hourly meteorological values for a simulated representative year based on data collected for years 1976 – 2005 (Wilcox and Marion, 2008). The tower placement subsystem involves analysis of the estimated location of Verizon cellular tower shelters suitable for GHP retrofitting based on the location of U.S. primary roads and population densities. A higher number of shelters are expected where major roads and high population clusters are collocated.

The hydrogeological subsystem incorporates soil and rock thermal properties for twelve groundwater regions in the U.S. Analyses of hydrogeological regions enabled thermal characterization of geological provinces based on expected rock types and groundwater occurrence within each region. The cost subsystem incorporates GHP market analysis, including installation costs for GHPs, state-level electricity prices, and available federal and state incentives for energy-efficient technology.

The environmental subsystem uses the Emissions & Generation Resource Integrated Database (eGRID) from the U.S. Environmental Protection Agency (EPA) to estimate indirect emissions from electricity purchases by EPA subregions (U.S. EPA, 2015). The annual CO_2 equivalent total output emission rates by EPA subregions were used to estimate the greenhouse gas (GHG) emissions generated as a result of electricity purchases from the grid to power cellular tower shelters.

Finally, the technical subsystem includes TRNSYS models validated using results from the Varna site to assess the performance of the GHP BHE field. The models use site-specific parameters including thermal properties of the soil/rock and grout, borehole installation design, and the coefficient of performance (COP) of the heat pump, among other parameters (Beckers et al., 2014; Beckers, 2016).

For the spatial analysis of the five subsystems, data gathering included collecting information from various sources and integrating data with varying spatial references, geometric formats, and attribute information. Modeling in ArcGIS involved building geoprocessing workflows and tools through ModelBuilder and Python-GIS.

4.2.2: National Weather Data Collection and Modeling

Variable and extreme weather conditions play a significant role in the heating and cooling loads of residential and commercial buildings (Baechler et al., 2010; Pertzborn et al., 2010; Stafford, 2013). In the U.S., the energy consumption of buildings for heating, ventilation, and air conditioning (HVAC) accounts for approximately 40% of the total building's energy use (U.S. EPA, 2016; U.S. EIA, 2017a; 2017b). For the nationwide modeling of the five cooling configurations presented in this study, weather conditions at each site are expected to significantly impact the operation and performance of the GHP, ASHP, AE, and DC units.

For modeling of building energy systems and renewable energy projects, the Typical Meteorological Year (TMY3) database from the National Renewable Energy Lab (NREL) National Solar Radiation Data Base (NSRDB) is often used to illustrate national weather conditions. The TMY3 dataset at each weather station includes 12 months (January – December), and contains hourly meteorological values based on simulations for the most typical months of the year over a period spanning from 1976 – 2005. The 12 typical months are selected based on the Sandia method, an empirical statistical approach that considers five important elements in the modeling of energy systems: global horizontal and direct normal radiations, dry bulb and dew point temperatures, and wind speed (Wilcox and Marion, 2008).

Since the TMY3 dataset represents typical rather than extreme weather conditions, the design of energy systems may be undersized for a particular extreme weather year (Wilcox and Marion, 2008; Pertzborn et al., 2010). Therefore, modeling results of building energy systems and renewable energy projects based on TMY files should not be used to design for peak loads and/or worst-case scenarios (Wilcox and Marion, 2008).

From Figure 4.2, a total of 925 TMY3 weather stations with different uncertainty classifications and data pool years (> 10 years) were used to characterize the contiguous U.S. climates. Along with the 925 stations, a total of 545 TMY3 weather boundaries are included in the dataset to typify areas that share similar climatic conditions. The 545 weather boundaries represent areal approximations of the weather conditions for a specific location based on the TMY3 weather stations (Wilcox and Marion, 2008; NREL, 2012).

Often, the TMY3 boundaries (areas) include more than one weather station. The TMY3 stations are assigned different uncertainty classifications depending on the periods of record of the data collected and simulated. Class I represent stations with the lowest uncertainty level and class III represent the highest. Class III stations might have incomplete periods of data records or may be missing important data elements used in the simulation of the weather files (Wilcox and Marion, 2008).

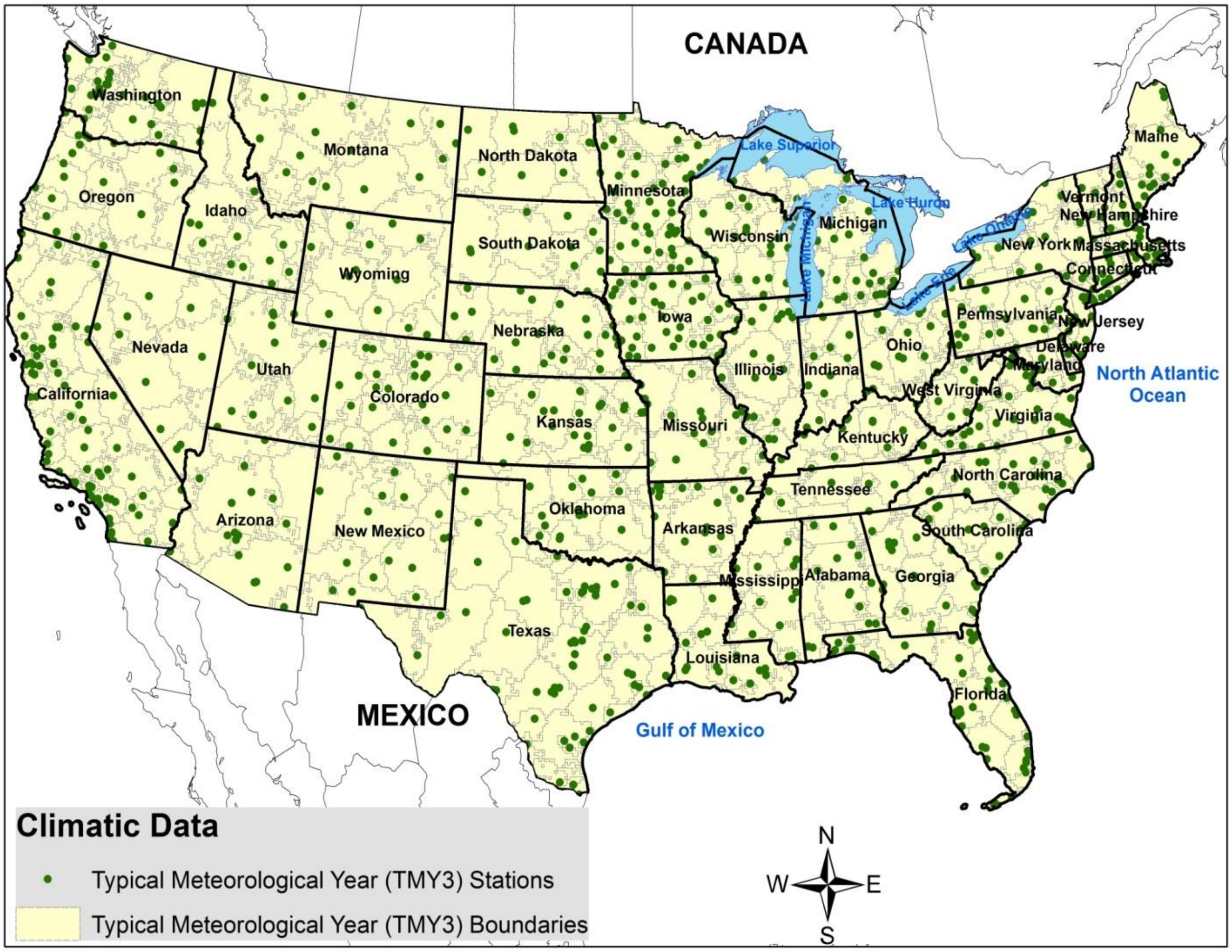

Figure 4.2 - Location of the TMY3 weather stations and corresponding boundaries (Wilcox and Marion, 2008; NREL, 2012).

For this study, the TMY3 stations with the lowest uncertainty (classes I and II) are used to represent each of the 545 weather boundaries defined by the NREL NSRDB (Wilcox and Marion, 2008; NREL, 2012). Nationwide climatic subdivisions, shown in Figure 4.3, were made based on the annual mean surface temperature of each of the 545 TMY3 weather boundaries. From Figure 4.3, Region A represents weather boundaries with annual mean surface temperatures of ≤ 4 °C. Regions B and C represent boundaries with annual mean surface temperatures of > 4 °C to ≤ 9 °C and > 9 °C to ≤ 15 °C, respectively. Regions D and E represent boundaries with annual mean surface temperatures of > 15 °C to ≤ 20 °C and > 20 °C to ≤ 26 °C, respectively. To compare the nationwide TEEP for cooling cellular tower shelters, several

TMY3 weather boundaries (areas) from each representative climatic subdivision in Figure 4.3 are simulated as described in sections 4.3 and 4.4.

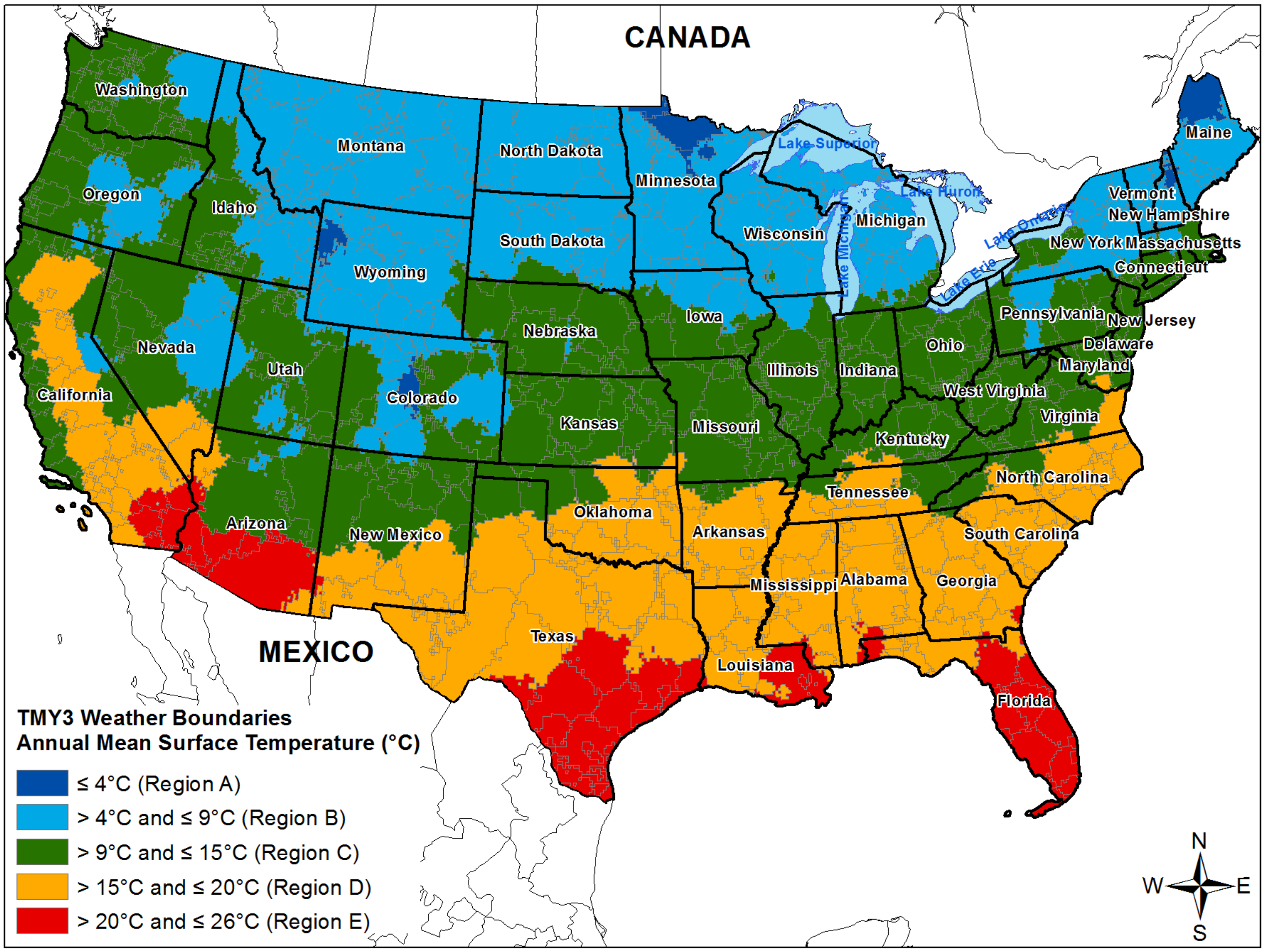

Figure 4.3 - Nationwide climatic subdivisions based on the Typical Meteorological Year (TMY3) weather boundaries of annual mean surface temperature (Wilcox and Marion, 2008; NREL, 2012).

The models developed by Beckers (2016) to simulate hybrid GHPs systems at the Varna site use the TMY3 dataset to determine operating conditions and performance of the GHP, AE, and DC units. For instance, the annual mean surface temperature (dry-bulb) from the weather station at Elmira Corning Regional Airport is used as a proxy for the initial underground and far-field temperatures of the BHE field. Furthermore, the DC unit at the Varna site operates when the outside temperatures are 5 °C above the mean annual surface temperature of the site

(Beckers, 2016). In this study, the TMY3 dataset is used to assess the long-term performance (20 years) of the five cooling configurations nationwide.

4.2.3: Tower Placement Data Collection and Modeling

Since 2011, the adoption of smartphones in the U.S. has more than doubled with over 70% of Americans currently owning a device (Smith, 2017). With a growing number of users, increased competition in telecommunication companies has accelerated the deployment of mobile networks, augmented capacity, and developed technologies to ensure robust and reliable network systems (Kashyap et al., 2014; Andersen, 2017).

Cellular towers are typically stand-alone facilities owned and installed by third-party companies. The towers are leased to individual telecommunication companies, and are shared by at least three companies (CTC, 2009). Each tenant owns and operates a cellular tower shelter and accompanying equipment used to transmit and process radio signals (American Tower, 2014). Factors that determine the placement of cellular towers include population and demographic data, proximity to major roads and highways, and availability of electrical power, among other factors (Harris, 2011).

Currently, Verizon Wireless estimates that over 18,000 cellular tower shelters across the nation could benefit from retrofitting their current inefficient ASHPs with hybrid GHP systems. The statewide estimates provided by Verizon do not include cabinet sites located outdoors and which utilize heat exchangers instead of ASHPs for cooling, and/or other lower cooling load sites that would not benefit from retrofitting with GHPs (Feeney, 2015; 2016).

In this study, the nationwide count of Verizon shelters to retrofit with hybrid GHPs was used in a geospatial analyses to collocate U.S. primary roads and regions with population densities above the U.S. average. As of 2011, the U.S. population density averaged 88.2 people per square mile (U.S. Census Bureau, 2012). The number of shelters is expected to be higher where major roads and high population clusters are collocated. From Figure 4.4, statewide estimates of Verizon shelters, location of major U.S. roads, and high population density areas are provided.

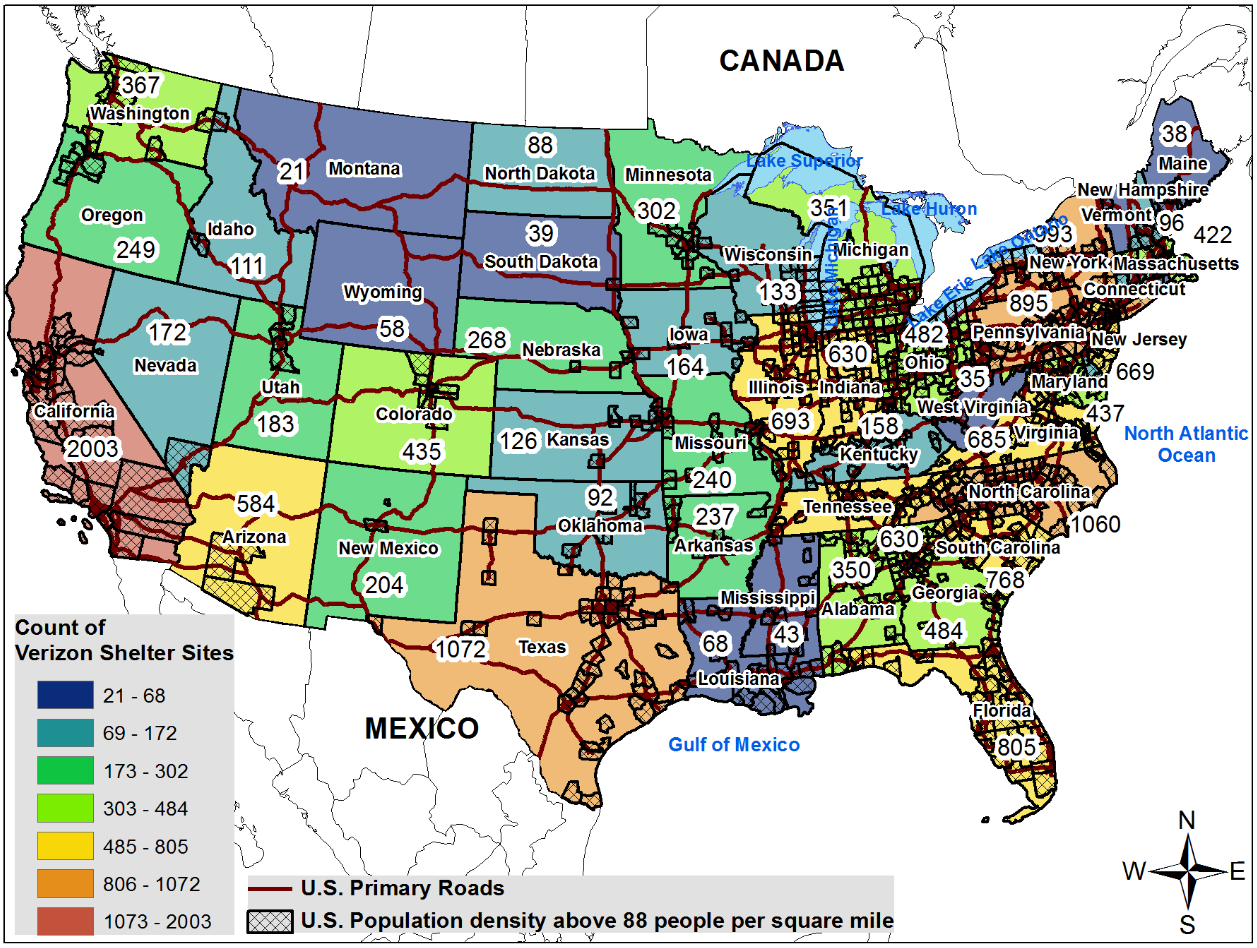

Figure 4.4 - Statewide estimates of Verizon Wireless cellular tower shelters collocated with U.S major roads and areas of high population density (U.S. Census Bureau, 2012; Feeney, 2015; 2016).

From Figure 4.4, states with high estimated counts of Verizon shelters include California, Texas, North Carolina, New York, and Pennsylvania, among others. States with low estimated shelter counts include Montana, Maine, and South Dakota, among others (Feeney, 2015; 2016).

As expected, states with high estimated shelter counts coincide with areas of high population density (above 88 people per square mile) and intersection of major roads. In sections 4.3 and 4.4, the TMY3 weather boundaries (areas) from each climatic subdivision (see Figure 4.3) that intersect major roads and high population densities are simulated based on the expectation that a higher number of shelters are located in these areas.

4.2.4: Hydrogeological Data Collection and Modeling

The characterization of the BHE field significantly influences the GHP design and affects the TEEP of the system. Specifically, the thermal properties of the ground, including the local geological and hydrological conditions, may determine the BHE loop length and the system's lifetime electricity consumption and environmental emissions (Liebel, 2012). For this reason, borehole thermal characterization is often performed during the design process and before installation of GHP systems.

To assess the thermal properties of the BHE field, several approaches are used including in-situ tests, laboratory measurements, and indirect methods (Brigaud et al., 1990; Clauser and Huenges, 1995). In-situ tests may include thermal response tests (TRT) to determine an average borehole effective thermal conductivity and thermal resistance. Typically, TRT measurements are performed over a period of 48 - 96 hours, and provide borehole thermal lumped-parameters that may include a combination of conduction and advection effects from groundwater flow (Beckers, 2016).

Laboratory measurements are performed when several samples of the borehole soil/rock materials are available. Often, laboratory measurements involve adjusting the conditions of the samples to represent the in-situ conditions of the field (Brigaud et al., 1990). Indirect methods are employed when no in-situ or laboratory measurements are available, and represent inferred thermal properties from literature review based on well-defined thermo-physical models (Clauser and Huenges, 1995).

Conducting hydrogeological characterization facilitates the identification of regional soil/rock types and groundwater-bearing units to provide estimates of the expected thermal conductivity at a site. Thermal conductivity is a measure of how effectively the borehole field soil/rock materials will conduct heat to and from the GHP circulating fluid. The presence of groundwater influences the effective thermal conductivity of boreholes because groundwater flow enhances heat dissipation. GHP systems in regions with groundwater flow may benefit from smaller installations and increased performance because groundwater thermally balances the BHE field in both cooling and heating applications (Diao et al., 2004).

At the Varna site, Beckers (2016) suggests that heat advection from groundwater flow resulted in a TRT effective thermal conductivity value four times higher than the reported value from laboratory measurements. Heat advection from groundwater flow is common in shallow geothermal systems, but often challenging to quantify and model. The challenges of advective heat transfer modeling in geothermal systems include limited data on the groundwater location, direction, and quantity (Beckers, 2016).

In this study, the nationwide hydrogeological characterization of GHP BHE fields only considers indirect methods to assess the ground thermal properties of the site. Due to the complexities of performing TRT or laboratory measurements nationwide, the hydrogeological characterizations presented in this section only represent first-order approximations of the site thermal properties. To increase the characterization of site-specific BHE fields, TRT and laboratory measurements on individual boreholes should be performed, as described in Beckers (2016).

To estimate the hydrogeological conditions across the contiguous U.S., twelve groundwater regions were used based on classifications by Thomas (1952) and Heath (1984). Each groundwater region contains information on the aquifer system and productivity, geological settings, and hydraulic characteristics. A subset of the geological and hydrological characteristics of each of the twelve groundwater regions from Thomas (1952) and Heath (1984) is presented in Table 4.1. In addition, the location of the twelve groundwater regions and their descriptions is provided in Figure A.1 of Appendix A.

Table 4.1 - Geological and hydrological characteristics of twelve groundwater regions presented by Thomas (1952) and Heath (1984).

Groundwater Regions		Components of the System		Characteristics of the Aquifer			Hydraulic Characteristics		
Region	**Name**	**Unconfined Aquifer**	**Confined Aquifer**	**Porosity Description**	**Porosity (-)**	**Brief Geological Setting**	**Transmissivity Description**	**Transmissivity (m^2/day)**	**Hydraulic Conductivity (m/day)**
1	Western Mountain Ranges	Minor aquifer	Not highly productive	Moderate	0.01-0.2	Mountains with thin soils over fractured rocks, alternating with narrow alluvial and glaciated valleys	Small	0.5-100	0.0003-15
2	Alluvial Basins	Dominant aquifer	Multiple productive aquifers	Large	>0.2	Thick alluvial deposits in basins and valleys bordered by mountains and locally of glacial origin	Large	20-20,000	30-600
3	Columbia Lava Plateau	Minor aquifer	Multiple productive aquifers	Small	<0.01	Thick sequence of lava flows irregularly interbedded with thin unconsolidated deposits and overlain by thin soils	Large	2,000-500,000	200-3,000
4	Colorado Plateau and Wyoming Basin	Hydrologically insignificant	Multiple productive aquifers	Small	<0.01	Thin soils over consolidated sedimentary rock	Small	0.5-100	0.003-2
5	High Plains	Dominant aquifer	Hydrologically insignificant	Large	>0.2	Thick alluvial deposits over fractured sedimentary rocks	Large	1,000-10,000	30-300
6	Nonglaciated Central Region	Minor aquifer	Multiple productive aquifers	Small	<0.01	Thin regolith over fractured sedimentary rocks	Moderate	300-10,000	3-300
7	Glaciated Central Region	Minor aquifer	Multiple productive aquifers	Moderate	0.01-0.2	Glacial deposits over fractured sedimentary rocks	Moderate	100-2,000	2-300
8	Piedmont and Blue Ridge	Minor aquifer	Not highly productive	Small	<0.01	Thick regolith over fractured crystalline and metamorphosed sedimentary rocks	Very Small	9-200	0.001-1
9	Northeast and Superior Uplands	Minor aquifer	Not highly productive	Small	<0.01	Glacial deposits over fractured crystalline rocks	Small	50-500	2-30
10	Atlantic and Gulf Coastal Plain	Minor aquifer	Multiple productive aquifers	Moderate	0.01-0.2	Complexly interbedded sand, silt, and clay	Moderate	500-10,000	3-100
11	Southeast Coastal Plain	Minor aquifer	Dominant Productive Aquifer	Large	>0.2	Thick layers of sand and clay over semi-consolidated carbonate rocks	Large	1,000-100,000	30-3,000
12	Alluvial Valleys	Dominant aquifer	Hydrologically insignificant	Large	>0.2	Thick sand and gravel deposits beneath floodplains and terraces of streams	Large	200-50,000	30-2,000

To estimate the expected soil/rock materials for each of the twelve groundwater regions described in Table 4.1, surficial and bedrock geological maps were collected and analyzed from the United States Geological Survey Earth Material website (Schruben et al., 1997; Soller et al., 2009; U.S.G.S, 2014). For this study, surficial (unconsolidated material) and bedrock units were categorized into five classifications: 1) unconsolidated materials; 2) sedimentary rocks; 3) volcanic rocks (igneous extrusive); 4) plutonic rocks (igneous intrusive); and 5) metamorphic rocks.

Assuming conduction-dominated heat transport in the BHE field, thermal properties for the five soil/rock classifications were assigned based on statistical geological groupings by Clauser and Huenges (1995) that used samples compiled by Birch and Clark (1940a,b), Clark (1966), Desai et al. (1974), Kappelmeyer and Hänel (1974), Roy et al. (1981), Čermák and Rybach (1982), and Robertson (1988). In Table 4.2, three thermal conductivity case studies are provided for each soil/rock classification based on the groupings by Clauser and Huenges (1995).

Table 4.2 - Three thermal conductivity case studies by rock classifications for conduction-dominated systems (Clauser and Huenges, 1995).

	Case A	**Case B**	**Case C**
Rock Class	**Thermal Conductivity, Lower (W/m·K)**	**Thermal Conductivity, Mean (W/m·K)**	**Thermal Conductivity, Upper (W/m·K)**
Unconsolidated, High Porosity	0.4	1.2	2.0
Sedimentary, Chemical	0.3	2.6	5.2
Sedimentary, Low Porosity	1.2	2.4	3.6
Igneous Extrusive, Low Porosity	1.5	2.9	4.3
Igneous Extrusive, High Porosity	1.1	1.9	2.7
Igneous Intrusive, Low Feldspar	1.8	3.0	4.2
Igneous Intrusive, High Feldpsar	1.8	2.6	3.4
Metamorphic, Low Quartz	1.7	2.9	4.1
Metamorphic, High Quartz	5.0	5.8	6.6

From Table 4.2, case study A corresponds to the lower range of thermal conductivities determined by subtracting two standard deviations away from the mean of the samples. Case study B corresponds to the mean thermal conductivity of the samples. Cases study C corresponds to the upper range of thermal conductivities determined by adding two standard deviations away from the mean of the samples.

The effects of groundwater flow on geothermal systems can be distinguished by using TRT measurements under well-characterized aquifer conditions. Liebel (2012) estimates that in fractured aquifers of sedimentary, igneous, and metamorphic rocks the TRT effective thermal conductivities may be on average 10 - 20% higher than thermal conductivity values determined by laboratory tests. The difference may be partially attributed to the fact that thermal conductivity from laboratory samples are often performed on dry samples and do not represent in-situ conditions (Liebel, 2012).

Huber and Arslan (2015) performed experimental, field, and numerical modeling on the effective thermal conductivity of unconsolidated materials under groundwater flow conditions considering various Darcy velocities. Darcy velocity is defined as the fluid flow per unit of cross sectional area in porous materials. Under low Darcy velocity groundwater flow (0 – 0.3 m/day), the effective thermal conductivities could be up to 25% greater than in conduction-only thermal conductivity measurements. Under velocities of 0.3 – 0.6 m/day, the effective thermal conductivities could be up to 50% greater than in conduction-only measurements. Under high Darcy velocities (> 0.6 m/day), the effective thermal conductivities could be as high as twice the value of conduction-only thermal conductivity measurements (Huber and Arslan, 2015).

To account for the effective thermal conductivity from groundwater advection in the twelve groundwater regions of Thomas (1952) and Heath (1984) (see Figure A.1 of Appendix A), the Péclet number was used as a threshold to determine when advection becomes significant in certain geological materials (Chiasson et al., 2000). The Péclet number (Pe) expresses the ratio of heat transport by bulk fluid motion to the heat transported by conduction. If the Péclet number exceeds one under groundwater presence, then heat advection may dominate over heat conduction within that geological material.

$$Pe = \frac{\rho_w \, c_w \, v_D \, n \, L}{K_{f,s}} \tag{4.1}$$

with Pe = dimensionless Péclet number (-), ρ_w = density of water (1000 kg/m^3), c_w = heat capacity of water (4180 J/kg·K), v_D = Darcy velocity (m/day), n = dimensionless porosity (-), L = typical borehole spacing (4.5 m), and $K_{f,s}$ = thermal conductivity (effective) of the soil/rock formation (W/m·K). The estimated porosity for each groundwater region was obtained from Heath (1984) (see Table 4.1). The effective thermal conductivity ($K_{f,s}$) for each rock classification is taken as the upper value for conduction-only (case study C in Table 4.2) to represent water-saturated samples.

For this study, the Péclet number was assessed under three Darcy velocity scenarios: 0.30 m/day, 0.60 m/day, and 1.64 m/day based on the geological and hydrological characteristics of each groundwater region described in tables 4.1 and 4.2. The Péclet number analysis for the twelve groundwater regions is provided in Table 4.3. For each groundwater region rock classification, the influences of groundwater advection were considered if the Péclet number exceeded a value of one under the three Darcy velocities aforementioned (Chiasson et al., 2000; Huber and Arslan, 2015).

Table 4.3 - Péclet number analysis for the twelve groundwater regions by Thomas (1952) and Heath (1984) based on three Darcy velocities.

Region	Groundwater Name	Rock Class	Case C Thermal Conductivity, Upper (W/m·K)	Porosity (-)	Pe>1, Velocity: 0.30 (m/day)	Pe>1, Velocity: 0.60 (m/day)	Pe>1, Velocity: 1.64 (m/day)
1	Western Mountain Ranges	Unconsolidated, High Porosity	2	0.01	No	Yes	Yes
		Sedimentary, Chemical	5.2	0.01	No	No	Yes
		Sedimentary, Low Porosity	3.6	0.01	No	No	Yes
		Igneous Extrusive, Low Porosity	4.3	0.01	No	No	Yes
		Igneous Extrusive, High Porosity	2.7	0.01	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.01	No	No	Yes
		Igneous Intrusive, High Feldpsar	3.4	0.01	No	No	Yes
		Metamorphic, Low Quartz	4.1	0.01	No	No	Yes
		Metamorphic, High Quartz	6.6	0.01	No	No	No
2	Alluvial Basins	Unconsolidated, High Porosity	2	0.2	Yes	Yes	Yes
		Sedimentary, Chemical	5.2	0.2	Yes	Yes	Yes
		Sedimentary, Low Porosity	3.6	0.2	Yes	Yes	Yes
		Igneous Extrusive, Low Porosity	4.3	0.2	Yes	Yes	Yes
		Igneous Extrusive, High Porosity	2.7	0.2	Yes	Yes	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.2	Yes	Yes	Yes
		Igneous Intrusive, High Feldpsar	3.4	0.2	Yes	Yes	Yes
		Metamorphic, Low Quartz	4.1	0.2	Yes	Yes	Yes
		Metamorphic, High Quartz	6.6	0.2	Yes	Yes	Yes
3	Columbia Lava Plateau	Unconsolidated, High Porosity	2	0.005	No	No	Yes
		Sedimentary, Chemical	5.2	0.005	No	No	No
		Sedimentary, Low Porosity	3.6	0.005	No	No	No
		Igneous Extrusive, Low Porosity	4.3	0.005	No	No	No
		Igneous Extrusive, High Porosity	2.7	0.005	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.005	No	No	No
		Igneous Intrusive, High Feldpsar	3.4	0.005	No	No	No
		Metamorphic, Low Quartz	4.1	0.005	No	No	No
		Metamorphic, High Quartz	6.6	0.005	No	No	No
4	Colorado Plateau and Wyoming Basin	Unconsolidated, High Porosity	2	0.005	No	No	Yes
		Sedimentary, Chemical	5.2	0.005	No	No	No
		Sedimentary, Low Porosity	3.6	0.005	No	No	No
		Igneous Extrusive, Low Porosity	4.3	0.005	No	No	No
		Igneous Extrusive, High Porosity	2.7	0.005	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.005	No	No	No
		Igneous Intrusive, High Feldpsar	3.4	0.005	No	No	No
		Metamorphic, Low Quartz	4.1	0.005	No	No	No
		Metamorphic, High Quartz	6.6	0.005	No	No	No
5	High Plains	Unconsolidated, High Porosity	2	0.2	Yes	Yes	Yes
		Sedimentary, Chemical	5.2	0.2	Yes	Yes	Yes
		Sedimentary, Low Porosity	3.6	0.2	Yes	Yes	Yes
		Igneous Extrusive, Low Porosity	4.3	0.2	Yes	Yes	Yes
		Igneous Extrusive, High Porosity	2.7	0.2	Yes	Yes	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.2	Yes	Yes	Yes
		Igneous Intrusive, High Feldpsar	3.4	0.2	Yes	Yes	Yes
		Metamorphic, Low Quartz	4.1	0.2	Yes	Yes	Yes
		Metamorphic, High Quartz	6.6	0.2	Yes	Yes	Yes
6	Nonglaciated Central Region	Unconsolidated, High Porosity	2	0.005	No	No	Yes
		Sedimentary, Chemical	5.2	0.005	No	No	No
		Sedimentary, Low Porosity	3.6	0.005	No	No	No
		Igneous Extrusive, Low Porosity	4.3	0.005	No	No	No
		Igneous Extrusive, High Porosity	2.7	0.005	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.005	No	No	No
		Igneous Intrusive, High Feldpsar	3.4	0.005	No	No	No
		Metamorphic, Low Quartz	4.1	0.005	No	No	No
		Metamorphic, High Quartz	6.6	0.005	No	No	No

Table 4.3 (continued) - Péclet number analysis for the twelve groundwater regions by Thomas (1952) and Heath (1984) based on three Darcy velocities.

Region	Groundwater Name	Rock Class	Case C Thermal Conductivity, Upper (W/m·K)	Porosity (-)	Pe>1, Velocity: 0.30 (m/day)	Pe>1, Velocity: 0.60 (m/day)	Pe>1, Velocity: 1.64 (m/day)
7	Glaciated Central Region	Unconsolidated, High Porosity	2	0.01	No	Yes	Yes
		Sedimentary, Chemical	5.2	0.01	No	No	Yes
		Sedimentary, Low Porosity	3.6	0.01	No	No	Yes
		Igneous Extrusive, Low Porosity	4.3	0.01	No	No	Yes
		Igneous Extrusive, High Porosity	2.7	0.01	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.01	No	No	Yes
		Igneous Intrusive, High Feldspar	3.4	0.01	No	No	Yes
		Metamorphic, Low Quartz	4.1	0.01	No	No	Yes
		Metamorphic, High Quartz	6.6	0.01	No	No	No
8	Piedmont and Blue Ridge	Unconsolidated, High Porosity	2	0.005	No	No	Yes
		Sedimentary, Chemical	5.2	0.005	No	No	No
		Sedimentary, Low Porosity	3.6	0.005	No	No	No
		Igneous Extrusive, Low Porosity	4.3	0.005	No	No	No
		Igneous Extrusive, High Porosity	2.7	0.005	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.005	No	No	No
		Igneous Intrusive, High Feldspar	3.4	0.005	No	No	No
		Metamorphic, Low Quartz	4.1	0.005	No	No	No
		Metamorphic, High Quartz	6.6	0.005	No	No	No
9	Northeast and Superior Uplands	Unconsolidated, High Porosity	2	0.005	No	No	Yes
		Sedimentary, Chemical	5.2	0.005	No	No	No
		Sedimentary, Low Porosity	3.6	0.005	No	No	No
		Igneous Extrusive, Low Porosity	4.3	0.005	No	No	No
		Igneous Extrusive, High Porosity	2.7	0.005	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.005	No	No	No
		Igneous Intrusive, High Feldspar	3.4	0.005	No	No	No
		Metamorphic, Low Quartz	4.1	0.005	No	No	No
		Metamorphic, High Quartz	6.6	0.005	No	No	No
10	Atlantic and Gulf Coastal Plain	Unconsolidated, High Porosity	2	0.01	No	Yes	Yes
		Sedimentary, Chemical	5.2	0.01	No	No	Yes
		Sedimentary, Low Porosity	3.6	0.01	No	No	Yes
		Igneous Extrusive, Low Porosity	4.3	0.01	No	No	Yes
		Igneous Extrusive, High Porosity	2.7	0.01	No	No	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.01	No	No	Yes
		Igneous Intrusive, High Feldspar	3.4	0.01	No	No	Yes
		Metamorphic, Low Quartz	4.1	0.01	No	No	Yes
		Metamorphic, High Quartz	6.6	0.01	No	No	No
11	Southeast Coastal Plain	Unconsolidated, High Porosity	2	0.2	Yes	Yes	Yes
		Sedimentary, Chemical	5.2	0.2	Yes	Yes	Yes
		Sedimentary, Low Porosity	3.6	0.2	Yes	Yes	Yes
		Igneous Extrusive, Low Porosity	4.3	0.2	Yes	Yes	Yes
		Igneous Extrusive, High Porosity	2.7	0.2	Yes	Yes	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.2	Yes	Yes	Yes
		Igneous Intrusive, High Feldspar	3.4	0.2	Yes	Yes	Yes
		Metamorphic, Low Quartz	4.1	0.2	Yes	Yes	Yes
		Metamorphic, High Quartz	6.6	0.2	Yes	Yes	Yes
12	Alluvial Valleys	Unconsolidated, High Porosity	2	0.2	Yes	Yes	Yes
		Sedimentary, Chemical	5.2	0.2	Yes	Yes	Yes
		Sedimentary, Low Porosity	3.6	0.2	Yes	Yes	Yes
		Igneous Extrusive, Low Porosity	4.3	0.2	Yes	Yes	Yes
		Igneous Extrusive, High Porosity	2.7	0.2	Yes	Yes	Yes
		Igneous Intrusive, Low Feldspar	4.2	0.2	Yes	Yes	Yes
		Igneous Intrusive, High Feldspar	3.4	0.2	Yes	Yes	Yes
		Metamorphic, Low Quartz	4.1	0.2	Yes	Yes	Yes
		Metamorphic, High Quartz	6.6	0.2	Yes	Yes	Yes

To assess the groundwater advection influence on thermal conductivity in groundwater regions with Péclet numbers greater than one, the estimates of the expected increase in the effective thermal conductivity by Liebel (2012) and Huber and Arslan (2015) were used. If the Péclet number exceeds a value of one, an increase in the effective thermal conductivity is assigned by multiplication with a factor that corresponds to the percent increase described in Huber and Arslan (2015) for unconsolidated sediments and in Liebel (2012) for all other rock classifications (see Table 4.4).

Table 4.4 - Proposed effective increase in thermal conductivities from groundwater advection under three Darcy velocities for various rock classifications (Liebel, 2012; Huber and Arslan, 2015).

	Case D	**Case E**	**Case F**
Rock Class	**Thermal Conductivity Groundwater Advection, Velocity: 0-0.3 (m/day)**	**Thermal Conductivity Groundwater Advection, Velocity: 0.3-0.6 (m/day)**	**Thermal Conductivity Groundwater Advection, Velocity: >0.6 (m/day)**
Unconsolidated Sediments (high porosity)	Thermal Conductivity (Upper, conduction) * 1.25	Thermal Conductivity (Upper, conduction) * 1.50	Thermal Conductivity (Upper, conduction) * 2
All others	Thermal Conductivity (Upper, conduction) * 1.10	Thermal Conductivity (Upper, conduction) * 1.15	Thermal Conductivity (Upper, conduction) * 1.20

A combination of conduction and advection heat transfer thermal conductivity cases result by joining tables 4.2 and 4.4. A summary of six thermal conductivity case studies by groundwater region and rock classification is presented in Table 4.5. For conduction-only dominated systems, the following case studies are presented: (A) lower range of thermal conductivities; (B) mean thermal conductivity; and (C) upper range of thermal conductivities. For advection-dominated systems, the following case studies are presented: (D) thermal conductivity under maximum Darcy velocity of 0.30 m/day; (E) thermal conductivity under maximum Darcy velocity of 0.60 m/day; and (F) thermal conductivity under maximum Darcy velocity of 1.64 m/day.

Table 4.5 - Summary of six thermal conductivity case studies by groundwater region and rock classifications.

			Case A	Case B	Case C	Case D	Case E	Case F
Ground-water Region	Groundwater Name	Rock Class	Conduction Only Thermal Conductivity, Lower (W/m·K)	Conduction Only Thermal Conductivity, Mean (W/m·K)	Conduction Only Thermal Conductivity, Upper (W/m·K)	Thermal Conductivity (W/m·K) Groundwater Advection, Velocity: 0.3 (m/day)	Thermal Conductivity (W/m·K) Groundwater Advection, Velocity: 0.6 (m/day)	Thermal Conductivity (W/m·K) Groundwater Advection, Velocity: 1.64 (m/day)
1	Western Mountain Ranges	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	3.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	6.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	4.3
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	5.2
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	5.0
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	4.1
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.9
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6
2	Alluvial Basins	Unconsolidated, High Porosity	0.4	1.2	2.0	2.5	3.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.7	6.0	6.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	4.0	4.1	4.3
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.7	4.9	5.2
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	3.0	3.1	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.6	4.8	5.0
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.7	3.9	4.1
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.5	4.7	4.9
		Metamorphic, High Quartz	5.0	5.8	6.6	7.3	7.6	7.9
3	Columbia Lava Plateau	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	2.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	5.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	3.6
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	4.3
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	4.2
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	3.4
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.1
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6
4	Colorado Plateau and Wyoming Basin	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	2.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	5.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	3.6
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	4.3
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	4.2
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	3.4
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.1
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6
5	High Plains	Unconsolidated, High Porosity	0.4	1.2	2.0	2.5	3.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.7	6.0	6.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	4.0	4.1	4.3
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.7	4.9	5.2
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	3.0	3.1	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.6	4.8	5.0
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.7	3.9	4.1
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.5	4.7	4.9
		Metamorphic, High Quartz	5.0	5.8	6.6	7.3	7.6	7.9
6	Nonglaciated Central Region	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	2.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	5.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	3.6
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	4.3
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	4.2
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	3.4
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.1
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6

Table 4.5 (continued) - Summary of six thermal conductivity case studies by groundwater region and rock classifications.

			Case A	Case B	Case C	Case D	Case E	Case F
Ground-water Region	Groundwater Name	Rock Class	Conduction Only Thermal Conductivity, Lower (W/m·K)	Conduction Only Thermal Conductivity, Mean (W/m·K)	Conduction Only Thermal Conductivity, Upper (W/m·K)	Thermal Conductivity (W/m·K) Groundwater Advection, Velocity: 0.3 (m/day)	Thermal Conductivity (W/m·K) Groundwater Advection, Velocity: 0.6 (m/day)	Thermal Conductivity (W/m·K) Groundwater Advection, Velocity: 1.64 (m/day)
7	Glaciated Central Region	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	3.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	6.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	4.3
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	5.2
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	5.0
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	4.1
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.9
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6
8	Piedmont and Blue Ridge	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	2.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	5.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	3.6
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	4.3
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	4.2
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	3.4
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.1
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6
9	Northeast and Superior Uplands	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	2.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	5.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	3.6
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	4.3
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	4.2
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	3.4
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.1
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6
10	Atlantic and Gulf Coastal Plain	Unconsolidated, High Porosity	0.4	1.2	2.0	2.0	3.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.2	5.2	6.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	3.6	3.6	4.3
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.3	4.3	5.2
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	2.7	2.7	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.2	4.2	5.0
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.4	3.4	4.1
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.1	4.1	4.9
		Metamorphic, High Quartz	5.0	5.8	6.6	6.6	6.6	6.6
11	Southeast Coastal Plain	Unconsolidated, High Porosity	0.4	1.2	2.0	2.5	3.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.7	6.0	6.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	4.0	4.1	4.3
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.7	4.9	5.2
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	3.0	3.1	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.6	4.8	5.0
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.7	3.9	4.1
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.5	4.7	4.9
		Metamorphic, High Quartz	5.0	5.8	6.6	7.3	7.6	7.9
12	Alluvial Valleys	Unconsolidated, High Porosity	0.4	1.2	2.0	2.5	3.0	4.0
		Sedimentary, Chemical	0.3	2.6	5.2	5.7	6.0	6.2
		Sedimentary, Low Porosity	1.2	2.4	3.6	4.0	4.1	4.3
		Igneous Extrusive, Low Porosity	1.5	2.9	4.3	4.7	4.9	5.2
		Igneous Extrusive, High Porosity	1.1	1.9	2.7	3.0	3.1	3.2
		Igneous Intrusive, Low Feldspar	1.8	3.0	4.2	4.6	4.8	5.0
		Igneous Intrusive, High Feldpsar	1.8	2.6	3.4	3.7	3.9	4.1
		Metamorphic, Low Quartz	1.7	2.9	4.1	4.5	4.7	4.9
		Metamorphic, High Quartz	5.0	5.8	6.6	7.3	7.6	7.9

In Section 4.3, the base case TEEP scenario for the hybrid GHP configurations consider conduction-only thermal conductivity estimates. Specifically, the thermal conductivity mean value (case study B) in Table 4.5 is used as a representative base case estimate for the rock classifications in each groundwater region. Section 4.4 provides a sensitivity analysis of the TEEP under various thermal conductivity estimates that consider heat transfer advection from groundwater flow.

4.2.5: Cost Data Collection and Modeling

To understand the potential market penetration of hybrid GHPs for cooling cellular tower shelters, the total cost of ownership (TCO) considers several factors including: 1) the current market for GHP installations; 2) average retail price of electricity for the commercial sector; and 3) available incentives offered to energy-efficient technologies.

Historically, increasing electricity prices in the U.S. and financial incentives have played a major role in the transition to a wider adoption of energy-efficient technologies, including GHP systems (Fouquet, 2016). Since 1978, geothermal systems have benefited from the creation of federal, state, and municipal incentives, rebates, and grants programs (Ellis, 2010). However, the magnitude and duration of these programs have varied from year-to-year, and the struggles to secure stimulus funds for geothermal technologies continue to date (Ellis, 2010; DSIRE, 2017).

In the U.S., surveys have been conducted to understand the market costs and benefits of GHP technologies (Liu et al., 2012; Battocletti and Glassley, 2013). In 2013, Battocletti and Glassley conducted a nationwide market analysis to over 360 companies associated with the design, manufacturing, and installation processes of GHP systems. Over 120 borehole heat exchanger (BHE) loop installers and 140 mechanical equipment installers provided estimates of the prices to install GHPs (Battocletti and Glassley, 2013). The results of the nationwide market analysis are summarized by census regions for the median price per length of BHE loop installed and the median capital cost per ton of GHP capacity installed, as shown in Figure 4.5.

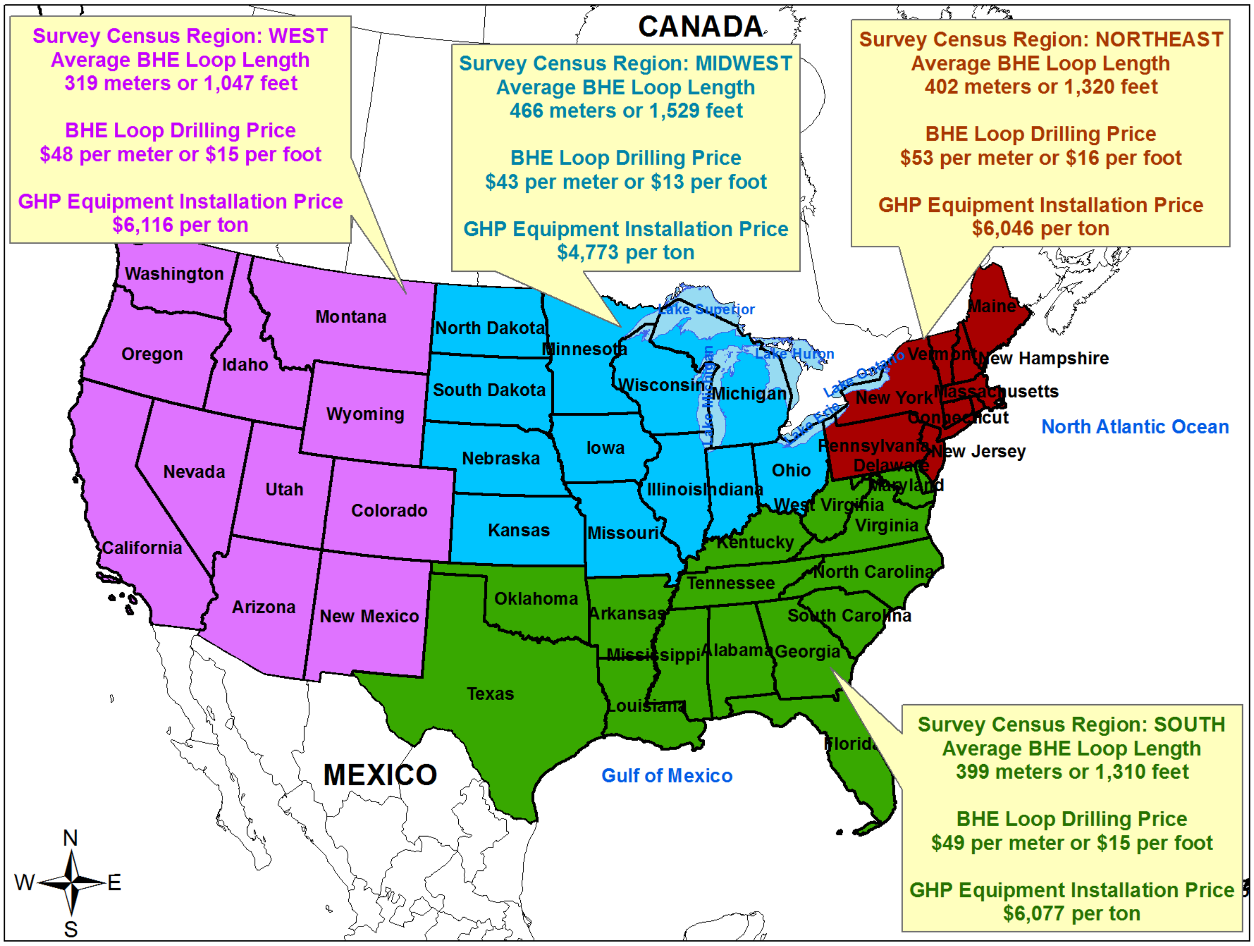

Figure 4.5 - Market analysis of the median price per length of BHE loop installed and median price per ton of GHP capacity installed by census regions (Battocletti and Glassley, 2013).

From Figure 4.5, the Midwest region shows the lowest median price per length of BHE loop installed ($13 per feet or $43 per meter), while the Northeast shows the highest ($16 per feet or $53 per meter). The survey results published by Battocletti and Glassley (2013) are in close agreement with the BHE loop installation cost at the Varna site ($15 per feet or $50 per meter). The total BHE loop length for the Varna site is almost 560 m (1,837 ft.) (Beckers, 2016).

The median price per ton of GHP capacity installed in the Midwest is over $4,700 per ton, while the West, Northeast, and South regions are around $6,000 per ton. The GHP equipment installation prices in Figure 4.5 could include pricing for interior piping, pumps, and ductwork, among other installation equipment (Battocletti and Glassley, 2013). For the Varna site, the GHP capital cost was estimated at $5,000 per unit and the cost for pumps, piping, and installation was $5,000. The Varna site uses two ClimateMaster TT026 GHP units, each consisting of 2 tons of installed capacity (ClimateMaster, 2005; Beckers, 2016).

The GHP market analysis presented by Battocletti and Glassley (2013) provides an initial estimate of variations in drilling prices and equipment installation prices by census regions. Regional market variations are expected to impact the nationwide TCO analysis of the five cooling configurations presented in this study. Even though GHP systems incur a high capital cost when compared to ASHPs (around $2,500 for a 2-ton system), the life expectancy of the GHP equipment and the BHE field is over 20 years (U.S. DOE, 2011; Beckers, 2016). The ASHP units are typically replaced after 10 years of service (Beckers, 2016).

Electricity prices in the U.S. have increased over the past 10 years and vary regionally by state, sector, and weather season. The electricity prices for residential and commercial consumers are higher than industrial consumers because the distribution costs for the former sectors are higher. In addition, high electricity prices are expected during the summer months nationwide because the electricity demand is greater for all sectors (U.S. EIA, 2017c).

In Figure 4.6, the average retail price for the commercial sector based on a 3-year average for years 2012 – 2014 is shown for the contiguous U.S. (U.S. EIA, 2015). The states of New York, Connecticut, Vermont, Massachusetts, and California have some of the highest average electricity prices for the contiguous U.S. (14 – 15 cents per kWh). In 2016, the U.S. average price of electricity was around 10.3 cents per kWh (U.S. EIA, 2017c). The states in dark green color have electricity prices lower than the 2016 U.S. average.

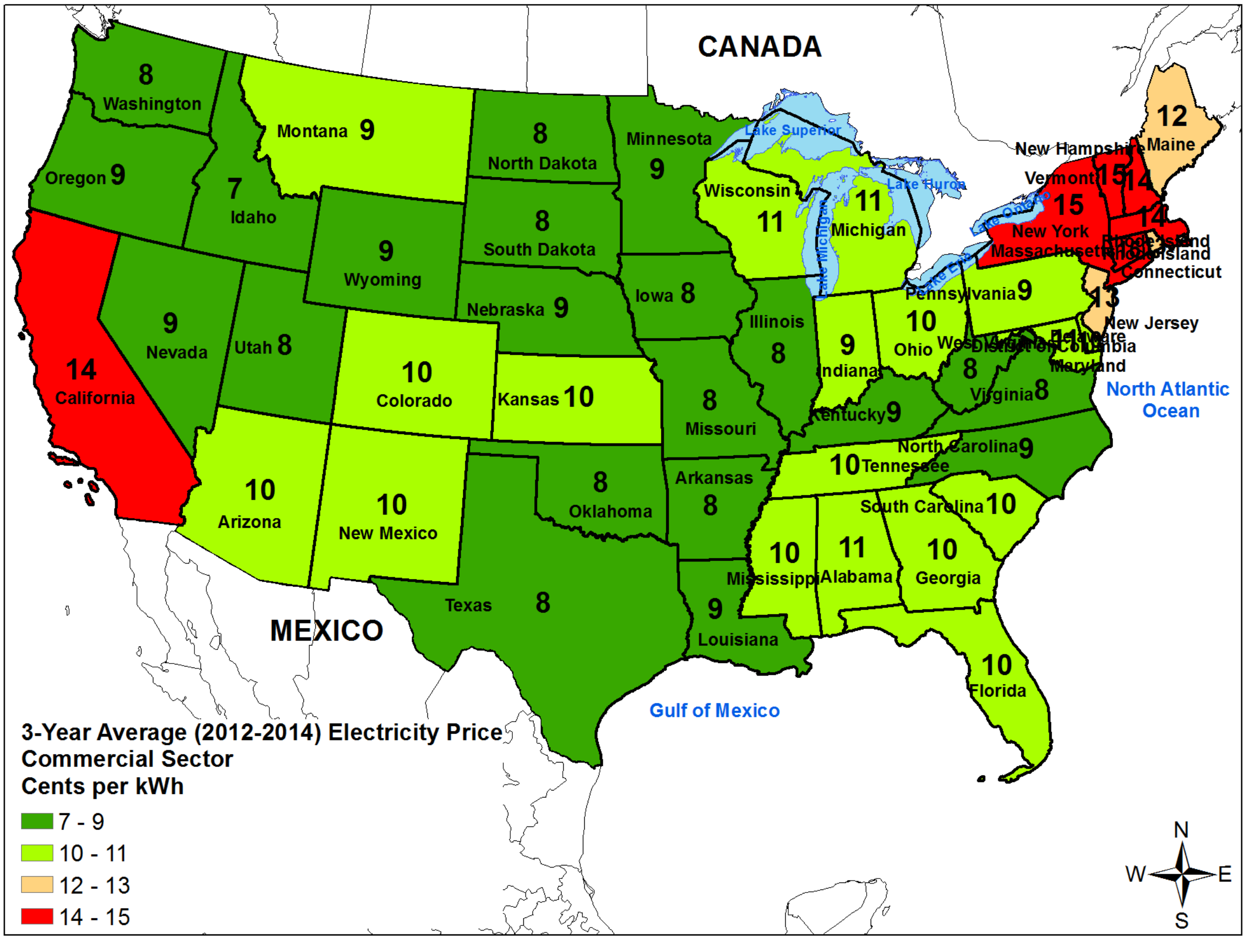

Figure 4.6 - Retail price of electricity (cents/kWh) for the commercial sector based on state-level 3-year average for years 2012 – 2014 (U.S. EIA, 2015).

The TCO includes capital expenditure and operating and maintenance costs throughout the lifetime of the cooling configurations. In this study, all of the cooling configurations consume electricity to operate. Therefore, the variability of electricity prices over the years and the efficiencies of the cooling configurations are expected to significantly impact the lifetime operating costs for both GHPs and ASHPs, especially in states with high electricity prices. The TCO for cooling configurations that consume large amounts of electricity and are located in states that have high electricity rates are expected to be higher, thus, lowering their economic attractiveness.

Existing and potential sources of incentives, rebates, and grants for energy-efficient technologies could favor the installation of GHPs over ASHPs. The Database of State Incentives for Renewables and Efficiency (DSIRE) operated by the North Carolina Clean Energy Technology Center at North Carolina State University lists a number of incentives for energy-efficient technologies in residential and commercial buildings (DSIRE, 2017).

At the federal level, a corporate depreciation has been offered to energy-efficient technologies, including GHP units, through the five-year Modified Accelerated Cost Recovery System (MACRS). This depreciation method is an annual tax deductible that allows accelerated recovery of the cost of energy-efficient technologies over the first few years of their lifetime. Recently, the federal government offered "bonus" depreciation for energy property placed in service from 2008 to 2013 in the amount of 50%. The remaining basis can then be depreciated in accordance to the five-year MACRS (ClimateMaster, 2014; DSIRE, 2017; IRS 2015).

Other available federal incentives include a Business Energy Investment Tax Credit of 10% for spending on energy-efficient property in service through the end of 2016. Also, Energy-Efficient Commercial Buildings Tax Deductions of up to $1.80 per sq. ft. have been offered to owners of commercial buildings that achieve a 50% annual energy cost savings compared to a reference building under the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards (ClimateMaster, 2014; DSIRE, 2017). Because incentives and rebates might vary from year-to-year, it is recommended to search for any relevant opportunities in the databases aforementioned before the design and installation of energy-efficient systems.

4.2.6: Environmental Emissions Data Collection and Modeling

Historically, electricity production in the U.S. has accounted for the largest source of greenhouse gas emissions (GHG), with carbon dioxide (CO_2) from fossil fuel combustion constituting most of the emissions (U.S. DOE, 2016). In 2016, roughly 35% of CO_2 was emitted by the U.S. electric power sector (U.S. EIA, 2018). Electricity purchases for cooling of cell tower shelters with conventional ASHP systems represent about 25% of the shelter's total energy consumption (Roy, 2008). The carbon footprint of operating and maintaining shelters throughout their lifetime (20 years) are expected to be significant.

The environmental performance of GHP systems are superior to ASHPs due to lower electricity consumption and higher overall system efficiencies. The U.S. General Accounting Office (GAO) estimates that GHPs can result in electricity savings of over 40% when compared to ASHPs, and over 70% when compared to traditional air-conditioning units and resistance heating equipment. Due to their high-energy efficiencies, GHPs produce some of the lowest CO_2, sulfur dioxide (SO_2), and nitrogen oxide (NO) emissions when compared to traditional HVAC systems (U.S. GAO, 1994).

Since 2009, Verizon Communications has implemented energy efficiency and sustainability programs to monitor and reduce their carbon footprint and energy costs. Specifically, Verizon has taken an operational approach to account and report the company's GHG inventory (Verizon, 2013a; 2013b, 2018; EY, 2015). Verizon's current GHG reporting standards are defined by "*The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard*". The reporting standards are based on a calendar year for all sources of emissions that include: Scope 1) direct emissions controlled or owned by the company; Scope 2) indirect emissions generated off-site, but purchased by the company; and Scope 3) other indirect emissions, including employee business travel by air or rail (Verizon, 2014; WRI, 2015a).

In this study, Scope 2 of the corporate reporting standards was evaluated because it considers electricity purchases by Verizon Wireless to power and cool cellular tower shelters nationwide. To assess the GHG emissions of cooling shelters based on Scope 2, the Emissions & Generation Resource Integrated Database (eGRID) from the U.S. Environmental Protection Agency (EPA) was used. The eGRID contains operational data for thousands of grid-connected power plants in the U.S. including GHG emission rates, generation resource mix, and fuel-specific heat input, among other data (Diem and Quiroz, 2012; U.S. EPA, 2015).

To define approximate geographic regions with similar GHG emission rates, generation resource mixes, and power grid transmission and distribution losses, the EPA uses representational areas called "subregions". As defined by the EPA, subregions represent a portion of the U.S. power grid contained within a single North American Electric Reliability Corporation (NERC) (U.S. EPA, 2015). Essentially, eGRID subregions are a subset of NERC regions and Power Control Areas (PCA) and are based on power plants and their transmission, distribution, and utility service territories (U.S. EPA, 2015). The NERC ensures the reliability and security of the American power system, and PCA balances and monitors electric power generation, load, and transmission (NERC, 2016; U.S. Homeland Security, 2016).

From Table 4.6 and Figure 4.7, 22 EPA subregions are used to define approximate geographic regions of the electric power system within the contiguous U.S. The emission rates and generation resource mixes representative of each subregion only take into account the power generation for that subregion regardless of any imported or exported electricity to other areas (U.S. EPA, 2015).

Table 4.6 - U.S. EPA eGRID 2012 subregions names and acronyms (U.S. EPA, 2015).

Subregion Acronym	U.S. EPA eGRID Subregion Name	Subregion Acronym	U.S. EPA eGRID Subregion Name
AZNM	Western Electric Coordinating Council - Southwest	RFCE	Reliability First Corporation - East
CAMX	Western Electric Coordinating Council - California	RFCM	Reliability First Corporation - Michigan
ERCT	Electric Reliability Council of Texas	RFCW	Reliability First Corporation - West
FRCC	Florida Reliability Coordinating Council	RMPA	Western Electric Coordinating Council - Rockies
MROE	Midwest Reliability Organization - East	SPNO	Southwest Power Pool - North
MROW	Midwest Reliability Organization - West	SPSO	Southwest Power Pool - South
NEWE	Northeast Power Coordinating Council - New England	SRMV	SERC Reliability Corporation - Mississippi Valley
NWPP	Western Electric Coordinating Council - Northwest	SRMW	SERC Reliability Corporation - Midwest
NYCW	Northeast Power Coordinating Council - NYC/Westchester	SRSO	SERC Reliability Corporation - South
NYLI	Northeast Power Coordinating Council - Long Island	SRTV	SERC Reliability Corporation - Tennessee Valley
NYUP	Northeast Power Coordinating Council - Upstate New York	SRVC	SERC Reliability Corporation - Virginia/Carolina

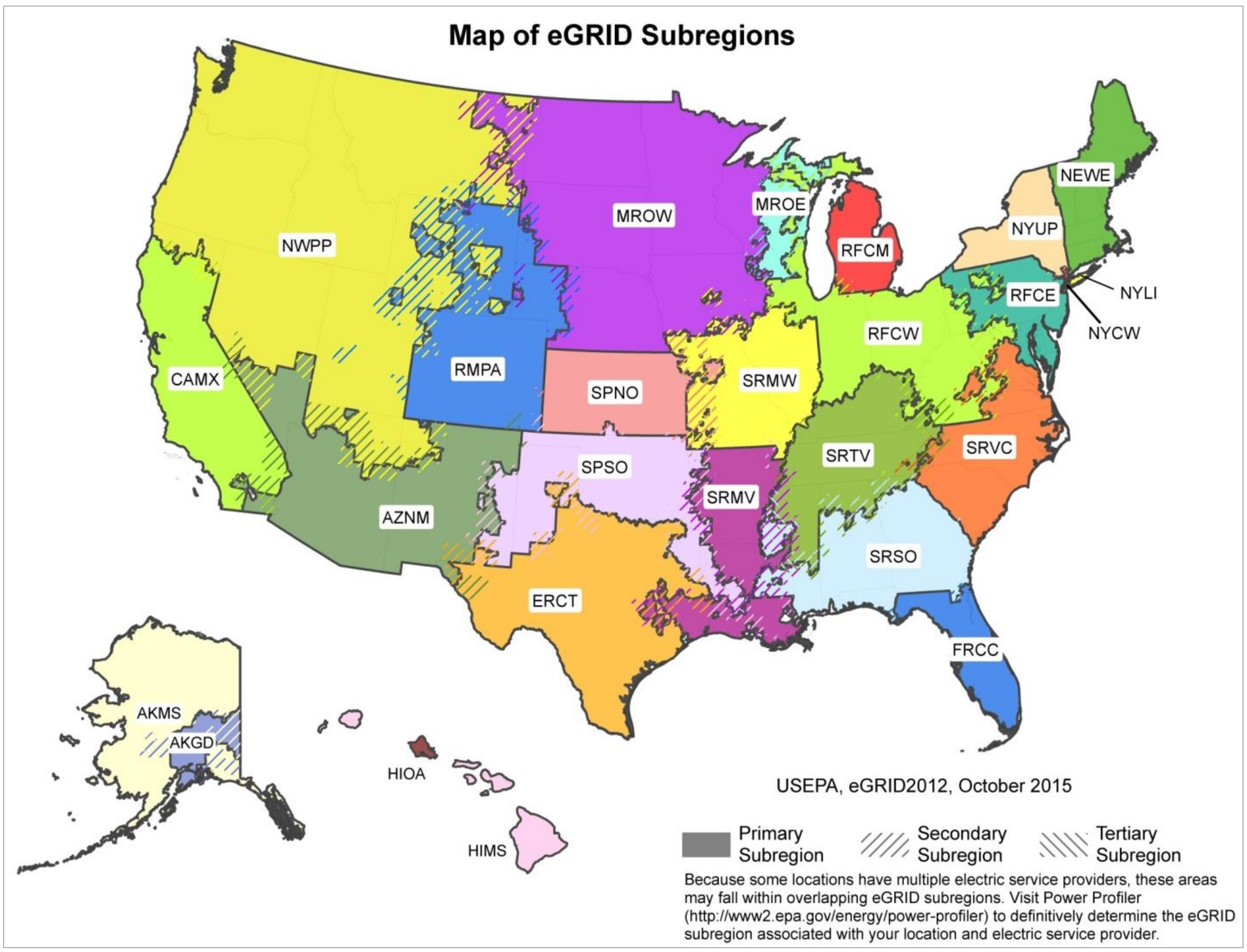

Figure 4.7 - U.S. EPA eGRID 2012 map of subregions (U.S. EPA, 2015).

To assess the nationwide environmental emissions by EPA subregion for the five cooling configurations presented in this study, the annual CO_2-equivalent (CO_2e) total output emission rates based on year 2012 data was used. The annual CO_2e total output emission rates measure the mass of the emissions as it relates to the net electricity generation output of a particular subregion in units of lb/MWh$_e$ or g/kWh$_e$ (Diem and Quiroz, 2012; U.S. EPA, 2015). According to Diem and Quiroz (2012), annual output emission rates are appropriate measures for GHG inventories and carbon footprinting.

Table 4.7 summarizes the annual CO_2e total output emission rates and generation resource mixes for the 22 subregions in Figure 4.7. From Table 4.7, the subregion with the highest annual CO_2e emission rate (832 g/kWh$_e$) is the Western Electric Coordinating Council/Rockies (RMPA), which comprises much of the state of Colorado and parts of Wyoming and Nebraska. The electricity generation resource mix of the RMPA subregion is primarily coal (~70%) and natural gas (~16%). The subregion with the lowest annual CO_2e emission rate (186 g/kWh$_e$) is the Northeast Power Coordinating Council/Upstate New York (NYUP), which comprises much of the state of New York. The electricity generation resource mix of the NYUP subregion is primarily natural gas (~30%), followed by hydro (~29%) and nuclear (~29%) (U.S. EPA, 2015).

The lifetime CO_2e estimates for the five cooling configurations provided in this study depend on the lifetime electricity consumption of each cooling configuration and the regional annual CO_2e emission rates. Therefore, regions with low electricity consumption but high CO_2e emission rates (per unit of electricity consumed) could result in higher lifetime CO_2e emissions than regions with high electricity consumption but low CO_2e emission rates.

Table 4.7 - U.S. EPA eGRID 2012 estimates of the annual CO_2e total output emissions rate (g/kWhe) and generation resource mix (%). Adapted from Table 5. eGRID2012 Subregion Resource Mix Summary Tables (U.S. EPA, 2015).

		Generation Resource Mix (%)										
Subregion Acronym	**Annual CO_2 equivalent total output emission rate (g/kWh_e)**	**Coal**	**Oil**	**Gas**	**Other Fossil Fuel**	**Nuclear**	**Hydro**	**Biomass**	**Wind**	**Solar**	**Geo-thermal**	**Other**
AZNM	526	37.4	0.1	33.9	0.0	18.0	6.3	0.3	1.0	0.7	2.4	0.0
CAMX	296	5.3	0.8	58.6	0.1	9.0	12.7	2.9	5.0	0.9	4.4	0.3
ERCT	521	30.5	1.0	49.1	0.1	10.7	0.1	0.2	8.3	0.0	0.0	0.1
FRCC	513	19.4	0.6	68.1	0.7	8.5	0.1	1.8	0.0	0.1	0.0	0.8
MROE	695	64.3	1.0	7.9	0.2	15.8	2.9	3.8	4.1	0.0	0.0	0.1
MROW	651	60.8	0.1	5.0	0.1	10.8	6.3	1.3	15.2	0.0	0.0	0.3
NEWE	292	3.0	0.3	51.9	1.7	30.0	5.9	6.1	1.1	0.0	0.0	0.1
NWPP	304	24.5	0.4	10.7	0.1	3.3	52.2	1.1	7.0	0.0	0.7	0.1
NYCW	317	0.0	0.2	61.7	0.4	37.2	0.0	0.5	0.0	0.0	0.0	0.0
NYLI	547	0.0	2.9	89.2	3.5	0.0	0.0	4.0	0.0	0.4	0.0	0.0
NYUP	186	5.5	0.2	30.4	0.4	28.9	29.2	1.8	3.6	0.0	0.0	0.0
RFCE	392	23.9	0.4	30.8	0.7	40.9	1.1	1.4	0.8	0.1	0.0	0.0
RFCM	716	58.6	0.4	24.9	0.8	11.9	0.0	2.0	1.8	0.0	0.0	0.0
RFCW	629	58.7	0.5	11.1	0.7	25.7	0.7	0.5	2.1	0.0	0.0	0.1
RMPA	832	70.4	0.0	16.6	0.0	0.0	3.2	0.1	9.4	0.3	0.0	0.1
SPNO	786	70.7	0.1	9.8	0.0	11.9	0.1	0.1	7.3	0.0	0.0	0.0
SPSO	702	48.4	0.8	39.4	0.2	0.0	2.0	1.5	7.6	0.1	0.0	0.0
SRMV	480	20.6	1.3	53.6	0.7	21.1	0.8	1.7	0.0	0.0	0.0	0.1
SRMW	781	75.4	0.1	6.9	0.1	15.1	0.2	0.1	1.9	0.0	0.0	0.2
SRSO	524	33.8	0.2	41.9	0.1	19.1	1.8	3.1	0.0	0.0	0.0	0.0
SRTV	610	53.7	0.7	15.5	0.0	22.3	6.9	0.8	0.0	0.0	0.0	0.0
SRVC	426	34.8	0.2	20.2	0.2	41.2	0.9	2.4	0.0	0.0	0.0	0.1

In this study, the lifetime CO_2e estimates for the five cooling configurations do not include upstream emissions associated with electricity generation in power plants. Upstream emissions could include fuel exploration, mining, processing and transporting, as well as power plant construction, operation, and decommissioning activities (Dones et al., 2003). A life-cycle assessment of the upstream and downstream GHG emissions could provide a more representative measure of the lifetime CO_2e estimates for cooling cellular tower shelters nationwide.

4.2.7: Technical Subsystem Modeling

In cooling-dominated applications, GHP systems may experience thermal imbalance in the BHE field over their lifetime due to continuous heat rejection to the ground. If thermal imbalance occurs, the GHP performance may degrade and an increase in the operating costs may result. Often, the BHE loop length is increased to prevent heat accumulation in the ground; however, increasing the loop length may significantly increase the capital expenditure of the systems (Fan et al., 2014). Coupling the GHP system with components that dissipate heat, such as air-side economizers (AE) or dry-coolers (DC), may help reduce the total cost of the system due to lower capital expenditure and lifetime operating and maintenance costs (Beckers, 2016).

Hybrid GHP systems in cooling-dominated climates have resulted in lower costs when operated during the cooler winter months. In most southern U.S. climates, hybrid GHPs can result in smaller BHE fields, stable ground temperatures, and increased GHP efficiencies over the lifetime of the system (Hackel et al., 2008; 2009). As shown by Beckers (2016), coupling AE with GHP or ASHP systems can supply cellular tower shelters with enough cooling to significantly reduce the capital and operating costs of these systems.

Chapter 4: Hybrid Geothermal Heat Pumps for Cooling Cellular Tower Shelters

For the five cooling configurations considered in this study, the models developed and validated by Beckers (2016) were used to assess the TEEP of cellular tower shelters located across various states. The hybrid GHP and ASHP models were developed in TRNSYS (Klein et al., 2010) and MATLAB (MathWorks, 2009) software based on thermodynamic and heat transfer principles, and using data collected at the Varna site and from literature sources (Beckers, 2016). This section briefly discusses the methodology for developing the hybrid GHP and ASHP models used in the SEM architecture for cooling shelters nationwide. Additional documentation on the demonstration site in Varna, and the hybrid GHP and ASHP modeling and validation efforts are provided in Beckers (2016) and Beckers et al. (2014).

From figures 4.8 and 4.9, the Verizon Wireless cellular tower station in Varna, NY shows the tower monopole, accompanying shelter housing the radio equipment, and BHE field located behind the shelter. The BHE field has six boreholes, four single-U BHEs each at a depth of 81 m (265 ft.) and two double-U BHEs each at a depth of 117 m (385 ft.). The total BHE length is roughly 560 m (1,837 ft.). The cooling configuration of the shelter consists of three GHPs, an AE, and a DC. In addition, the Varna site includes monitoring wells and a number of sensors to monitor the performance of the hybrid GHP system to provide the data needed for validation of the numerical models (Beckers, 2016).

At the Varna site, the AE allows cold outside air into the shelter when the ambient dry-bulb temperature drops below the set-point temperature of 10 °C. When the AE is running, the GHP system shuts down allowing the BHE field to thermally recover as no heat rejection from the shelter into the ground is occurring. Frequent use of AEs increases the risks of dust particle accumulation in the electronics. Therefore, air filters in AE are replaced on a regular basis, which increases maintenance costs of the hybrid GHP and ASHP systems (Beckers, 2016).

The DC is an air-cooled heat exchanger located outside the shelter and connected to the BHE field. A glycol solution is circulated between the DC and the BHE field during cold days allowing for active cooling of the reservoir ("recharging"). The recharging of the BHE field with the DC may offset any thermal imbalance in the field during warm months, and enhance the long-term performance of the GHP system in cooling-dominated applications. At the Varna site, the DC configuration is used when the ambient temperature drops below 15 °C (59 °F) (Beckers, 2016). DCs are typically operated in the temperature range of 2.8 – 5.6 °C (5 – 10 °F) above the ambient dry-bulb temperature (Williams, 2016).

Figure 4.8 – Photograph of the Verizon Wireless cellular tower station in Varna, NY (Beckers, 2016).

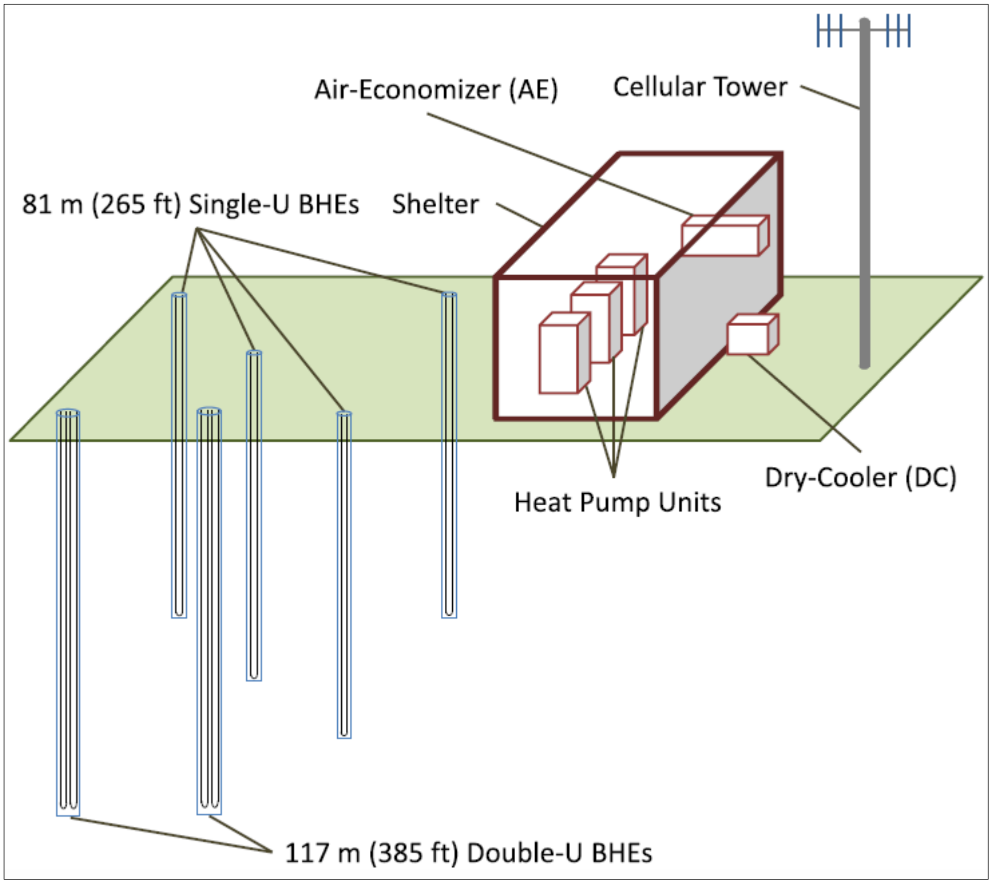

Figure 4.9 – Schematic of the Verizon Wireless cellular tower monopole, shelter with cooling equipment, and geothermal borehole heat exchanger field (BHE) (Beckers, 2016).

The numerical models developed and validated by Beckers (2016) include TRNSYS models for five cooling configurations: 1) GHP-only; 2) GHP + AE; 3) GHP + DC; 4) ASHP-only; and 5) ASHP + AE. ASHPs were considered in the cooling configurations to enable a TEEP comparison of retrofitting ASHPs with GHPs, since the current nationwide business-as-usual (BAU) cooling method is with ASHP systems. Figure 4.10, shows a schematic of the TRNSYS model for case 1) GHP-only. The TRNSYS models for cases 2 – 5 are included in Figures A.2 – A.5 of Appendix A.

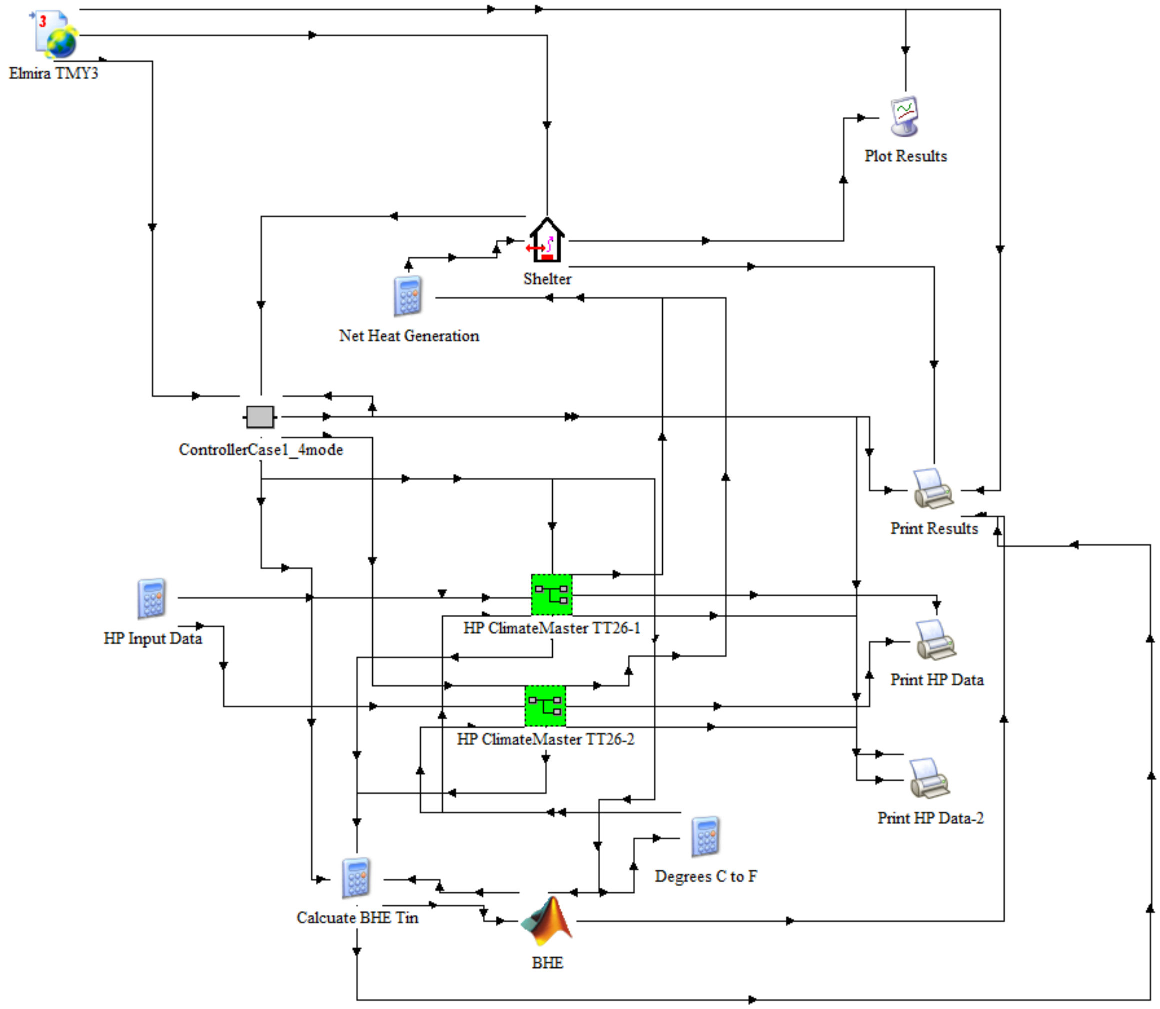

Figure 4.10 – Schematic of the TRNSYS model for case 1: geothermal heat pump (GHP)-only for cooling of cellular tower shelters (Beckers, 2016).

From Figure 4.10, the weather component uses the TMY3 dataset to estimate the annual hourly dry-bulb temperature of the site, as described in Section 4.2.2. The shelter is represented by a single-zone lumped capacitance building model in TRNSYS, with parameter values such as thermal capacitance derived from measured data at the Varna site. For all cooling configurations, the GHP, AE, DC, and ASHP units are modeled using correlations based on the manufacturers' datasheets. Descriptions and correlations of all TRNSYS components are furthered documented in Beckers (2016).

For the GHP cases, the BHE is represented using transient heat transfer models based on g-functions and finite difference models implemented in MATLAB and coupled with TRNSYS software. G-functions are functions used to describe temperature response factors at the BHE wall caused by continuous and constant heat pulses for different BHE field geometries. The models of various individual components, including GHP and BHE, have been validated or are directly based on measured data at the Varna site (Beckers, 2016).

Embedded in the model are certain parameters specific to the Varna site, including thermal properties of the soils, rocks, and grout, borehole installation design, and coefficient of performance (COP) of the GHP units, among others (Beckers, 2016). However, some of the site-specific parameters, including the thermal properties of soils and rocks, are expected to change for the nationwide analysis of the five cooling configurations, as furthered described in Section 4.3.

For model validation purposes, the TRNSYS simulation incorporates site-specific ambient temperatures, heat pump inlet temperatures, and equipment heat generation measured at the Varna site. The equipment heat generation of cellular tower shelters can vary from 8 to 11 kW_{th} (Beckers, 2016). However, a representative heat generation for shelters across the nation was set at 8 kW_{th} (Feeney, 2015; 2016). The BHE model assumes a conduction-only thermal reservoir because of the complexities of measuring, monitoring, and modeling groundwater advection in geothermal reservoirs. Due to the complexities aforementioned, the circulating fluid supply temperature in the BHE model is based on the Varna site measurements (Beckers, 2016).

In Section 4.3, a base case scenario of the TEEP for five cooling configurations across various states are evaluated and compared by considering the nationwide characterization discussed in sections 4.2.2 – 4.2.6, and the techno-economic modeling efforts in Section 4.2.7. Specifically, the base case scenario includes the technical models and parameters discussed in this section, but considers variations in the parameters with consideration to weather, hydrogeology, costs, and environmental emissions across the nation.

4.3: Case Studies of the Technical, Economic, and Environmental Performance (TEEP) of Five Cooling Configurations

The work presented in this section evaluates and compares the TEEP of five cooling configurations nationwide. Specifically, the case studies include simulation results from the SEM geospatial nationwide characterization and techno-economic modeling provided in Section 4.2. The objectives of this section are to provide a TEEP base case scenario for five cooling configurations that consider regional variations from the data collected and modeled both at the Varna site and nationwide. The five cooling configurations include: 1) GHP-only; 2) GHP + AE; 3) GHP + DC; 4) ASHP-only (BAU); and 5) ASHP + AE.

A summary of the base case parameters for the TEEP evaluation and comparison is provided for each cooling configuration in Table 4.8. The base case parameters were earlier introduced in Section 4.2 for the nationwide analysis and in Beckers (2016) for the Varna site. The performance metrics for the five cooling configurations include the total cost of ownership (TCO), lifetime (20 years) electricity consumption (LEC), and lifetime CO_2-equivalent emissions (LCO_2e).

The TCO includes the total capital (CAP) costs of each system plus the lifetime operation and maintenance (LOM) costs. The TCO is calculated by using the life cycle cost (LCC) financial performance metric:

$$TCO = \sum_{y=0}^{lt} \frac{CF_y}{(1+dr-ir)^y} \tag{4.2}$$

with TCO = total cost of ownership ($M), CF_y = cash flow in year y ($), lt = expected lifetime of the system (20 years), $dr - ir$ = net discount rate, where dr = discount rate and ir = inflation rate. It is assumed that the CAP costs of each cooling configuration are incurred in year zero (y = 0). The costs incurred during the subsequent years (y = 1 – 20) represent the annual operation and maintenance costs. The annual operation and maintenance costs include electricity costs for operating and maintenance costs for servicing the systems (Beckers, 2016). For this study, the discount and inflation rates are 5% and 2%, respectively, throughout the lifetime of the systems.

For each cooling configuration, the LEC considers the electricity consumption of heat pump units (GHP or ASHP), circulation pumps for GHP configurations-only, AE, and DC units (Beckers, 2016). The LCO_2e considers the CO_2e total output emission rates from Table 4.7 in Section 4.2.6 and the LEC for each cooling configuration.

Table 4.8 – Base case parameters for the evaluation of the technical, economic, and environmental performance (TEEP) of five cooling configurations.

<table>
<tr><th colspan="2"></th><th colspan="5">Cooling Configuration</th></tr>
<tr><th>Parameter</th><th>Metric</th><th>Case 1: GHP-only</th><th>Case 2: GHP + AE</th><th>Case 3: GHP + DC</th><th>Case 4: ASHP-only (BAU)</th><th>Case 5: ASHP + AE</th></tr>
<tr><td>Shelter Heat Generation</td><td>Technical</td><td colspan="5">8 kW_{th} *(Section 4.2.7)*</td></tr>
<tr><td>Weather Data</td><td>Technical</td><td colspan="5">TMY3 weather stations and boundaries *(Figures 4.2 and 4.3 in Section 4.2.2)*</td></tr>
<tr><td>Hydrogeologic Data</td><td>Technical</td><td colspan="3">Mean conduction-only thermal conductivity estimates based on surficial and bedrock geologic maps for the U.S. *(Table 4.5 in Section 4.2.4)*</td><td colspan="2"></td></tr>
<tr><td>AE Setpoint</td><td>Technical</td><td></td><td>10°C *(Section 4.2.7)*</td><td colspan="2"></td><td>10°C *(Section 4.2.7)*</td></tr>
<tr><td>DC Setpoint</td><td>Technical</td><td colspan="2"></td><td>5°C above mean annual surface temperature *(Section 4.2.7)*</td><td colspan="2"></td></tr>
<tr><td>System Lifetime</td><td>Technical</td><td colspan="5">20 years *(Beckers, 2016)*</td></tr>
<tr><td>Net Discount Rate</td><td>Economic</td><td colspan="5">3% *(Beckers, 2016)*</td></tr>
<tr><td>Electricity Rate</td><td>Economic</td><td colspan="5">EIA 3-year average (years 2012 - 2014) for the commercial sector *(Figure 4.6 in Section 4.2.5)*</td></tr>
<tr><td>Drilling Capital Cost</td><td>Economic</td><td colspan="3">National market analysis median price per length of BHE loop installed *(Figure 4.5 in Section 4.2.5)*</td><td colspan="2"></td></tr>
<tr><td>GSHP Unit Capital Cost</td><td>Economic</td><td colspan="3">$5,000 (two units for redundancy) *(Beckers, 2016)*</td><td colspan="2"></td></tr>
<tr><td>GSHP capital cost for pumps, piping & installation</td><td>Economic</td><td colspan="3">$5,000 *(Beckers, 2016)*</td><td colspan="2"></td></tr>
<tr><td>ASHP Unit Capital Cost</td><td>Economic</td><td colspan="3"></td><td colspan="2">$2,500 (two units for redundancy) *(Beckers, 2016)*</td></tr>
<tr><td>AE Capital Cost</td><td>Economic</td><td></td><td>$1,000 *(Beckers, 2016)*</td><td></td><td></td><td>$1,000 *(Beckers, 2016)*</td></tr>
<tr><td>DC Capital Cost</td><td>Economic</td><td colspan="2"></td><td>$1,000 *(Beckers, 2016)*</td><td colspan="2"></td></tr>
<tr><td>GSHP Maintenance Cost</td><td>Economic</td><td colspan="3">$200/year *(Beckers, 2016)*</td><td colspan="2"></td></tr>
<tr><td>ASHP Maintenance Cost</td><td>Economic</td><td colspan="3"></td><td colspan="2">$580/year *(Beckers, 2016)*</td></tr>
<tr><td>AE Maintenance Cost</td><td>Economic</td><td></td><td>$200/year *(Beckers, 2016)*</td><td colspan="2"></td><td>$200/year *(Beckers, 2016)*</td></tr>
<tr><td>Incentives</td><td>Economic</td><td colspan="5">None</td></tr>
<tr><td>Environmental Emissions</td><td>Environmental</td><td colspan="5">EPA eGRID year 2012 tables and maps *(Table 4.7 in Section 4.2.6)*</td></tr>
</table>

The TEEP for the five cooling configurations was estimated by modeling the nationwide characteristics of individual TMY3 weather boundaries (areas) that intersect major roads and high population density areas. For each TMY3 weather boundary, estimates of the regional annual mean surface temperature (T_o), formation thermal conductivity ($K_{f,s}$), CAP and maintenance costs, and CO_2e total output emission rates were obtained. The TMY3 weather boundaries were selected for modeling because each subsystem in Section 4.2 characterized the nation according to different geospatial analysis of the sampled data collected.

For instance, the hydrogeological modeling (see Section 4.2.4) provided estimates of the formation "effective" thermal conductivity based on groundwater regions defined by Thomas (1952) and Heath (1984). The estimated BHE loop drilling costs (see Section 4.2.5) for GHP configurations were obtained from assembled national surveys, and are summarized by census regions defined by Battocletti and Glassley (2013). Electricity rates (see Section 4.2.5) are summarized for each individual state from EIA estimates (U.S. EIA, 2015). Finally, environmental emissions rates (see Section 4.2.6) are provided by subregions as defined by the U.S. EPA (2015).

For TMY3 weather boundaries that intersected multiple regional subsystems (groundwater, census, states, or EPA subregions), a representative value for that subsystem was obtained by averaging all the values that fell within the weather boundary. Therefore, estimates presented in this section for each particular subsystem represent approximations of the expected regional values based on the available data obtained and the geospatial analysis. To increase the spatial resolution at a particular location, it is necessary to perform detailed hydrogeological and climatic analyses, as well as establish economic and environmental metrics that are representative of that location.

For each GHP configuration (cases 1 – 3), the techno-economic simulation times using TRNSYS-MATLAB interfaces for individual TMY3 weather boundaries were on the order of 2.5 hours per simulation. The simulation time constraint for GHP configurations limited the number of simulations performed within a reasonable timeframe. Therefore, only 269 TMY3 weather boundaries were simulated for each GHP configuration. In contrast, the simulation times of ASHP cooling configurations (cases 4 – 5) were on the order of 2 – 3 minutes per weather boundary. All 545 TMY3 weather boundaries were simulated for both ASHP case studies.

For cases 1 – 3, the weather boundaries selected for simulation were based on the tower placement subsystem analysis discussed in Section 4.2.3. TMY3 weather boundaries that intersected major roads and high population density areas (areas above 88 people per square mile) were selected for simulation. It is expected that a higher number of Verizon Wireless cell tower shelters are located in areas of high population density (Feeney, 2015; 2016).

Sections 4.3.1 – 4.3.5 provide TEEP results for cases 1 – 5 summarized based on nationwide climatic subdivisions presented in Figure 4.3 of Section 4.2.2. In Section 4.3.6, the TEEP for six geographic locations in the U.S. representative of various climatic regions are evaluated and compared.

4.3.1: Case 1: Geothermal Heat Pump (GHP) – only

Since climate is expected to play a significant role in the performance of GHP systems, the 269 TMY3 weather boundaries (areas) simulated for case 1 were divided into five climatic regions (see Figure 4.3 of Section 4.2.2). TRNSYS-MATLAB simulations were performed for a number of weather boundaries within each climatic region to model a representative total BHE length that provided a coefficient of performance (COP) of at least 3.5. Due to differences in climatic and hydrogeological characteristics, the total BHE lengths and COP varied by climatic region.

In figures 4.11 and 4.12, a summary of the technical performance (total BHE length and COP) for the 269 weather boundaries simulated in the five climatic regions is presented. For cooling-dominated applications, weather boundaries located in areas with low T_0 and high $K_{f,s}$ result in small BHE field installations. Similarly, areas with high T_0 and low $K_{f,s}$ require a higher number of boreholes and/or longer borehole depths. From Figure 4.11, weather boundaries in Region A are characterized by $T_0 \leq 4$ °C and $K_{f,s}$ of 2.5 - 3.0 W/m·K, and require a total BHE length of up to 160 m (2 boreholes each at a depth of 80 m). On the other hand, weather boundaries in Region E are characterized by $T_0 > 20$ °C and $K_{f,s}$ of 1.8 - 2.5 W/m·K, and may require up to 8 boreholes each at a depth of 135 m for a total BHE length of over 1,000 m.

From Figure 4.12, weather boundaries requiring small BHE fields are located in the states of Maine, New Hampshire, and Minnesota, among others. Weather boundaries requiring large BHE installations are located in parts of Florida, Louisiana, Texas, and Arizona, among others. The size of the BHE field largely affects the total cost of ownership (TCO), which includes the capital (CAP) costs and lifetime operation and maintenance (LOM) costs. Factors that affect market penetration of GHP systems often include high installation costs from drilling of the BHE fields.

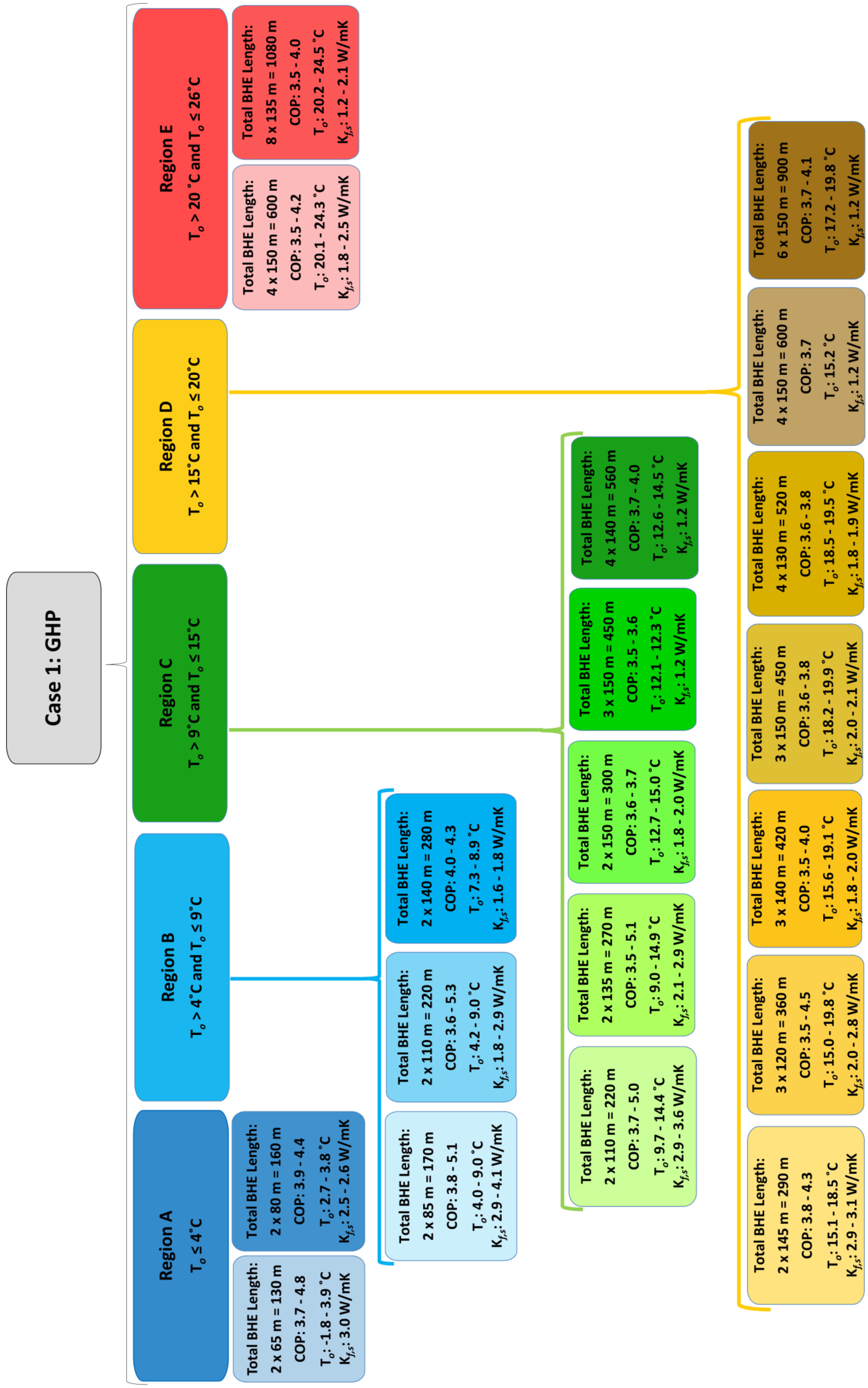

Figure 4.11 - Summary of the technical performance for 269 weather boundaries simulated in the five climatic subdivisions for case 1: GHP - only.

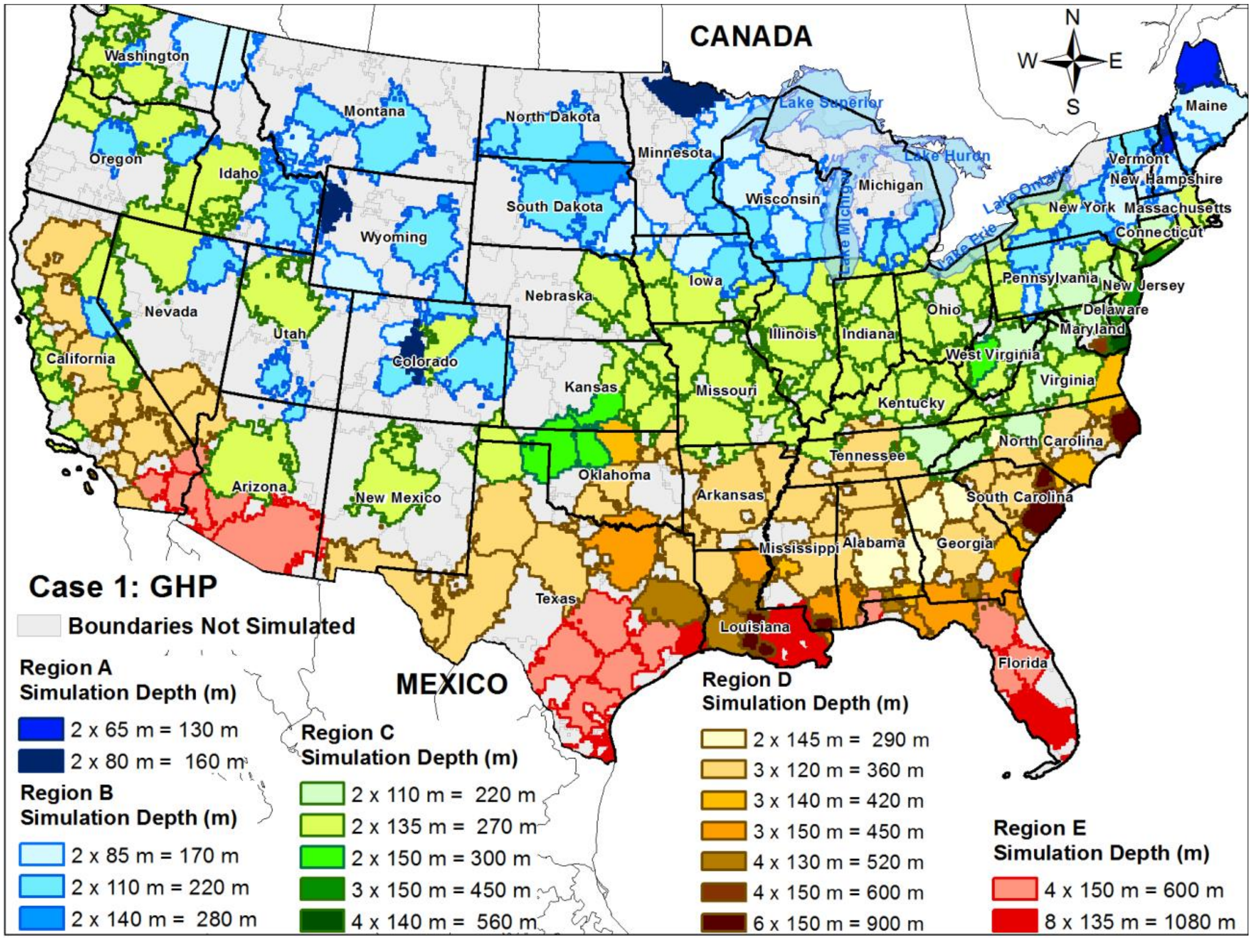

Figure 4.12 - Map of the total borehole (BHE) length (m) for 269 simulated weather boundaries in five climatic subdivisions for case 1: GHP - only.

The TEEP performance for weather boundaries simulated in case 1 are provided in Table 4.9 based on the climatic subdivisions presented in Figure 4.11. From Table 4.9, the CAP costs increase with increasing total BHE length. In regions A and B, the CAP costs are the lowest and range from $21,800 - $29,700. In regions C and D, CAP costs range from $25,800 - $44,500 and $29,200 - $59,100, respectively. The highest CAP costs are estimated in areas of high cooling loads (Region E), which can range from $43,800 - $67,900.

Table 4.9 - Summary of the technical, economic, and environmental performance (TEEP) for 269 weather boundaries simulated in five climatic subdivisions for case 1: GHP - only.

Region	Total BHE Length (m)	Total Cost of Ownership (TCO) ($1,000)	Capital (CAP) Cost ($1,000)	Lifetime O&M (LOM) Cost ($1,000)	Lifetime Electric Consumption (LEC) (MWhe)	Lifetime CO_{2e} Emissions (LCO_2e) (tons)	Lifetime Average COP	Simulated Boundaries
A	2 x 65 m = 130 m	50.8 - 56.1	21.8	29.0 - 34.2	263.2 - 353.8	76.8 - 103.3	3.7 - 4.8	2
A	2 x 80 m = 160 m	45.0 - 46.7	21.8 - 22.7	22.3 - 24.0	292.8 - 332.2	188.6 - 243.5	3.9 - 4.4	3
B	2 x 85 m = 170 m	42.0 - 64.8	22.2 - 23.9	19.8 - 40.8	258.3 - 348.8	83.4 - 247.8	3.8 - 5.1	19
B	2 x 110 m = 220 m	42.7 - 66.6	24.4 - 26.6	17.1 - 40.0	247.1 - 370.3	61.0 - 286.1	3.6 - 5.3	41
B	2 x 140 m = 280 m	50.5 - 67.7	26.9 - 29.7	23.0 - 38.0	309.1 - 325.1	57.6 - 265.7	4.0 - 4.3	3
C	2 x 110 m = 220 m	47.9 - 66.3	25.8 - 26.6	22.1 - 39.7	265.3 - 362.2	54.5 - 190.5	3.7 - 5.0	18
C	2 x 135 m = 270 m	45.8 - 70.0	26.5 - 29.2	18.5 - 42.0	261.2 - 378.9	53.1 - 284.4	3.5 - 5.1	85
C	2 x 150 m = 300 m	54.9 - 56.1	27.8 - 29.2	26.1 - 28.4	362.8 - 375.4	224.9 - 279.1	3.6 - 3.7	4
C	3 x 150 m = 450 m	71.7 - 83.5	37.6 - 38.7	34.1 - 44.8	373.8 - 377.8	146.4 - 206.2	3.5 - 3.6	3
C	4 x 140 m = 560 m	71.9 - 82.2	42.4 - 44.5	29.4 - 37.8	336.2 - 368.9	140.8 - 144.5	3.7 - 4.0	2
D	2 x 145 m = 290 m	52.1 - 60.1	29.2	22.9 - 30.8	311.4 - 359.0	161.3 - 188.1	3.8 - 4.3	5
D	3 x 120 m = 360 m	54.4 - 76.4	31.1 - 32.6	21.7 - 44.1	302.1 - 388.8	92.4 - 263.3	3.5 - 4.5	40
D	3 x 140 m = 420 m	58.7 - 66.8	34.2 - 35.6	24.5 - 31.3	340.9 - 390.6	142.4 - 253.5	3.5 - 4.0	6
D	3 x 150 m = 450 m	60.7 - 67.7	37.1	23.7 - 30.7	355.8 - 378.9	178.6 - 217.5	3.6 - 3.8	6
D	4 x 130 m = 520 m	65.6 - 70.4	40.5	25.1 - 29.9	359.5 - 380.6	188.4 - 224.8	3.6 - 3.8	5
D	4 x 150 m = 600 m	72.8	44.4	28.4	362.9	148.3	3.7	1
D	6 x 150 m = 900 m	83.2 - 87.4	59.1	24.0 - 28.3	331.1 - 374.2	141.0 - 221.0	3.7 - 4.1	6
E	4 x 150 m = 600 m	67.5 - 85.5	43.8 - 44.4	23.1 - 41.7	330.3 - 392.0	149.8 - 204.2	3.5 - 4.2	14
E	8 x 135 m = 1080 m	93.0 - 96.9	67.9	25.1 - 29.0	350.4 - 401.3	172.4 - 209.0	3.5 - 4.0	6

The LOM costs vary significantly by region because these costs are dictated by variations in statewide electricity rates (see Figure 4.6 in Section 4.2.5). High electricity prices are observed in California, New York, and New England states. Most New England states are located in regions A and B, expected to have small BHE field installations. However, due to high electricity prices in some regions of A and B, the LOM costs may surpass the CAP costs of installing GHP systems. Furthermore, electricity prices below the 2016 U.S. average of 10.3 cents per kWh are observed in many regions of D and E. In Region E with a total BHE length of over 1,000 m, the LOM costs are in the range of $25,100 - $41,700. The LOM costs of Region E are comparable to regions with cool climates (regions A and B).

As expected, the lifetime electric consumption (LEC) of the simulated weather boundaries are high in regions with high cooling loads (regions D and E). Overall, LEC increases with increasing total BHE length and can surpass 400 MWhe in Region E. The lifetime CO_2e emissions (LCO_2e) is a function of the LEC of the GHP system and the annual CO_2e total output emission rates by EPA eGRID subregions (see Table 4.7 and Figure 4.7 in Section 4.2.6). The output emission rates reflect the generation resource fuel mix of each subregion. High LCO_2e emissions are observed in several weather boundaries of regions B, C, and D, and can surpass 286 tons of CO_2e.

In Figure 4.13, the TCO is provided for each simulated weather boundary based on climatic and total BHE length subdivision outline in Table 4.9. TCO for regions A and B ranges from \$45,000 - \$56,100 and \$42,000 - \$67,700, respectively. For regions C and D, the TCO ranges from \$45,800 - \$83,500 and \$52,100 - \$87,400, respectively. The highest TCO is observed in Region E, and can range from \$67,500 - \$96,900.

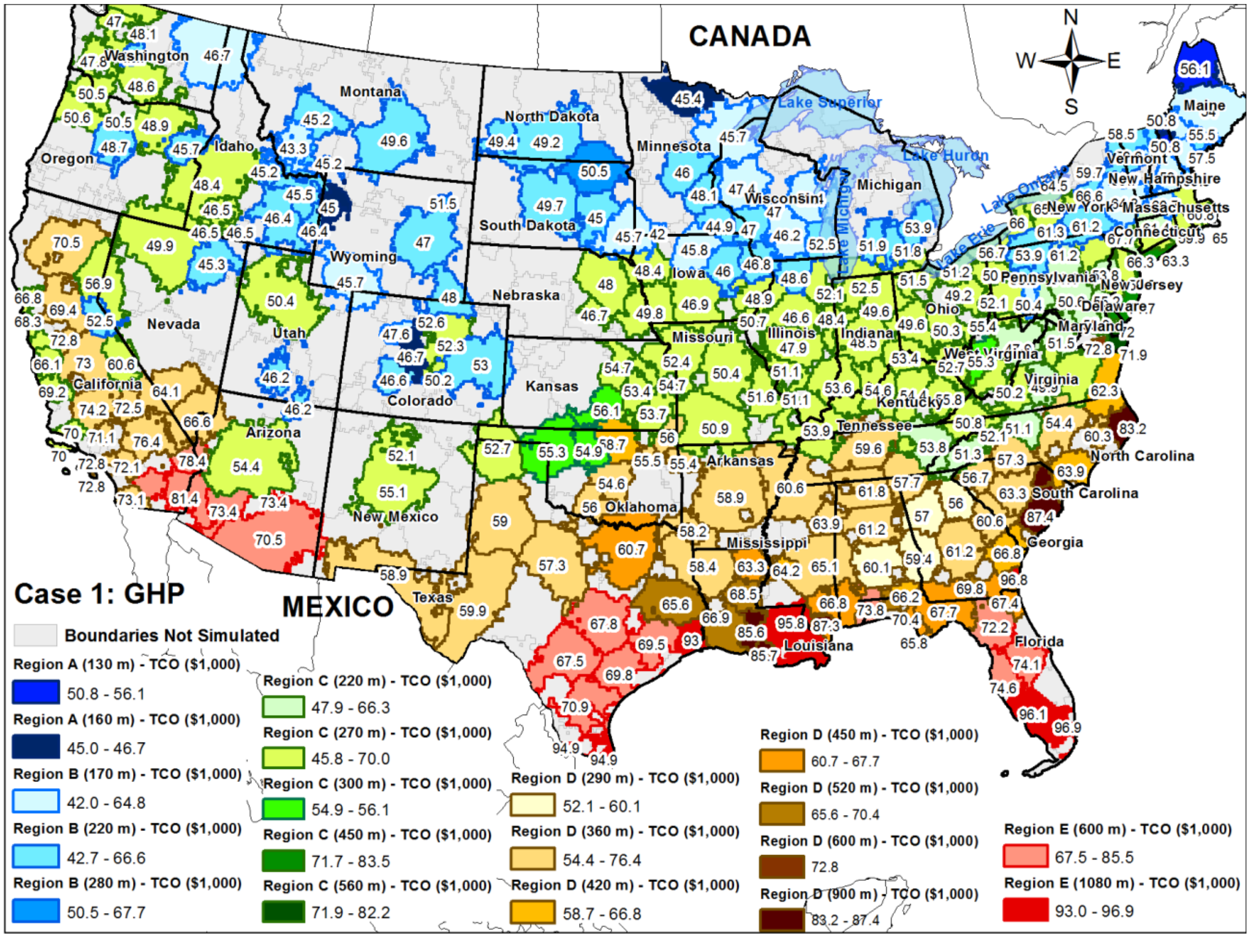

Figure 4.13 - Map of the total cost of ownership (TCO) for 269 simulated weather boundaries based on climatic and total BHE length subdivision for case 1: GHP - only.

Informed by the TEEP results of the 269 TMY3 weather boundaries simulated in figures 4.11 – 4.13 and Table 4.9, estimates were made for boundaries not simulated due to time constraints. A similar approach to the one presented in Figure 4.11 was made for the remaining 276 TMY3 weather boundaries. Weather boundaries falling within a specified range of T_0 and $K_{f,s}$ were classified according to Figure 4.14 and a total BHE length was estimated based on simulated boundaries with similar characteristics.

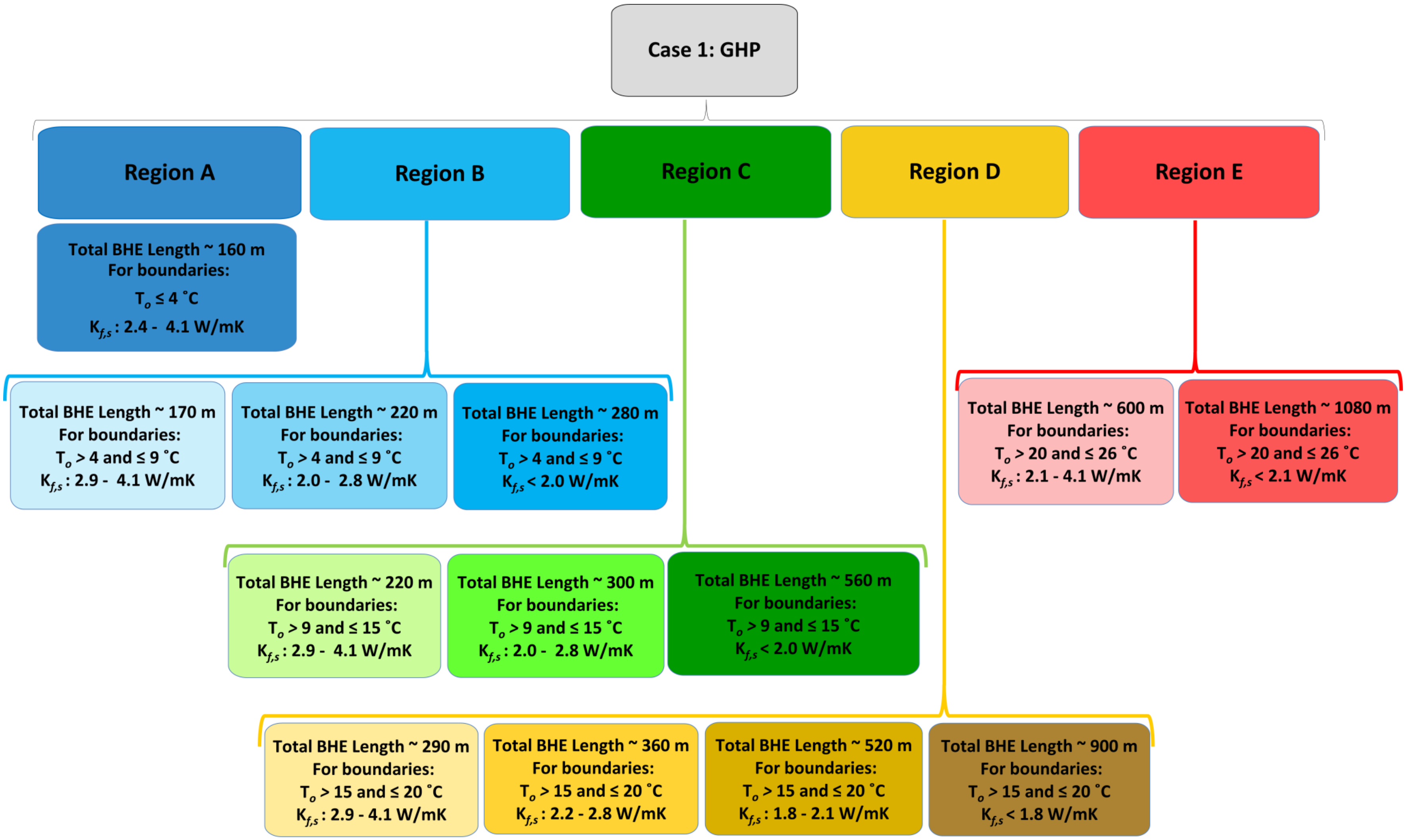

Figure 4.14 - Nationwide generalizations used to estimate the technical, economic, and environmental performance (TEEP) of all 545 TMY3 weather boundaries based on simulation results of the 269 weather boundaries presented in Figure 4.11 for case 1: GHP-only.

From Figure 4.14, weather boundaries in Region A corresponding to $T_0 \leq 4$ °C and $K_{f,s}$ of 2.4 – 4.1 W/m·K were estimated to have a total BHE length of 160 m. In Region B with $T_o > 4$ °C and ≤ 9 °C and $K_{f,s} < 2.0 – 4.1$ W/m·K, the total BHE length ranges from 170 – 280 m. In Region C with $T_o > 9$ °C and ≤ 15 °C and $K_{f,s} < 2.0 – 4.1$ W/m·K, the total BHE length ranges from 220 – 560 m. In Region D with $T_o > 15$ °C and ≤ 20 °C and $K_{f,s} <1.8 – 4.1$ W/m·K, the total BHE length ranges from 290 – 900 m. In Region E with $T_o > 20$ °C and ≤ 26 °C and $K_{f,s} < 2.1 – 4.1$ W/m·K, the total BHE length ranges from 600 – 1080 m.

The generalizations in Figure 4.14 were used to summarize the nationwide TEEP of case 1 (GHP-only) based on regional climatic subdivisions and thermal soil/rock properties. In Figure 4.15, summary results of the TCO, CAP and LOM costs, LEC, LCO_2e, and lifetime average COP are provided. Overall, lower TCO is expected in cooler regions (A and B) and higher TCO in warmer regions (C, D, and E) because climate significantly affects the performance of GHPs for cooling-dominated applications. Geothermal BHE field installations in warm climates are expected to be larger than in cool climates, significantly increasing the CAP costs of the system.

The TEEP results in Figure 4.15 vary regionally and are summarized by the total BHE installation length. For instance, Region A results in the lowest TCO, CAP costs, and LEC for all regions because of small BHE field installations (total BHE length of 160 m). On the other hand, Region E results in the highest TCO, CAP costs, and LEC for all regions because BHE installation fields can exceed 1,000 m of total length. Nationwide LOM costs and LCO_2e emissions vary significantly by region because of variations in statewide electricity rates and EPA subregion generation resource fuel mix, respectively.

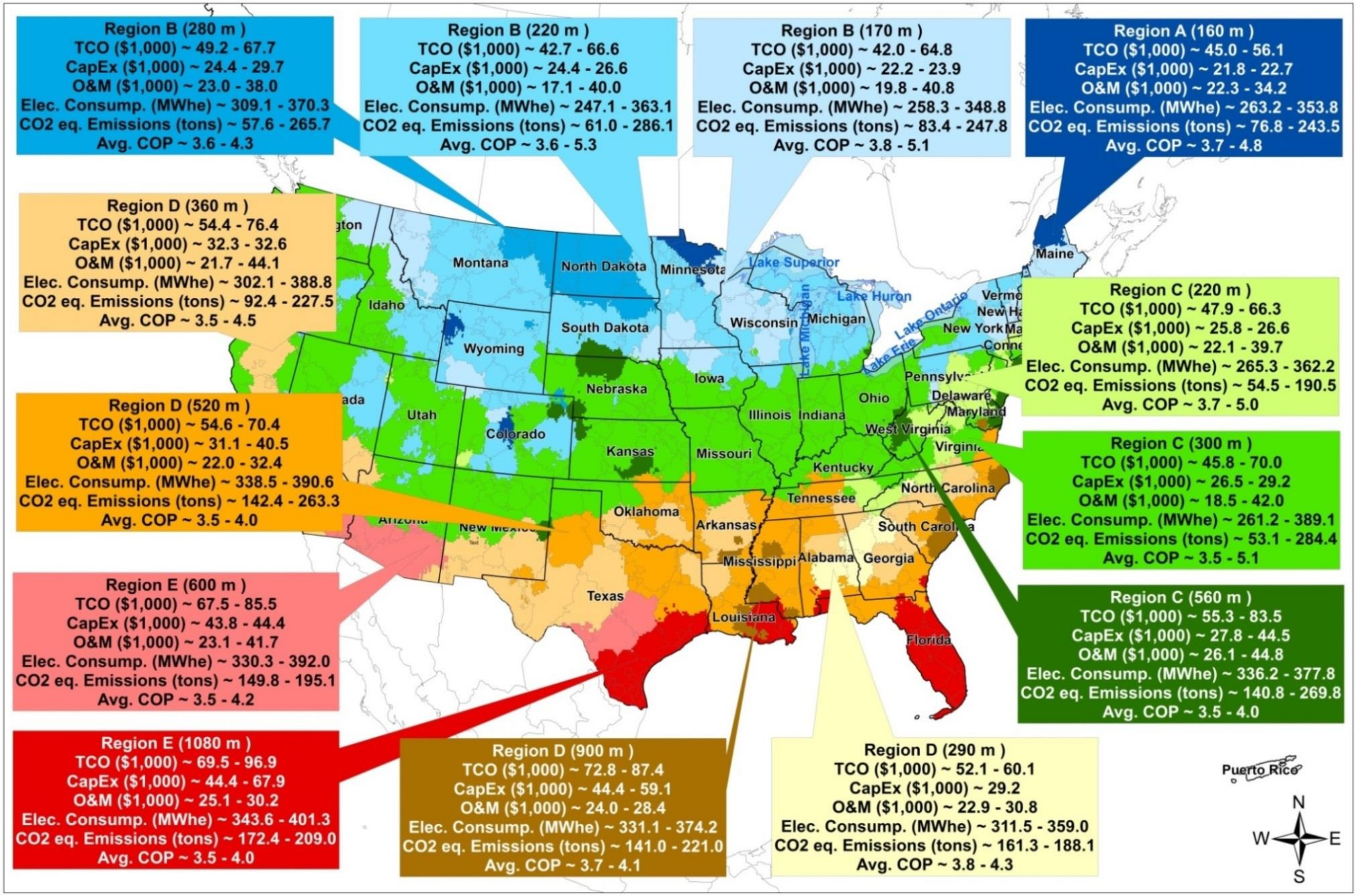

Figure 4.15 - Nationwide technical, economic, and environmental performance (TEEP) results by climatic region from generalizations presented in Figure 4.14 for case 1: GHP-only.

4.3.2: Case 2: Geothermal Heat Pump (GHP) + Air Economizer (AE)

The TEEP simulations for case 2 were performed similarly to case 1 (GHP-only) in section 4.3.1. From figures 4.16 and 4.17, a summary of the technical performance, including total BHE length and COP, for the 269 weather boundaries simulated in case 2 is presented. For regions A, B, and C, the total BHE length is smaller and COP is larger when compared to case 1 because of the advantages of employing AE units in cooler climatic regions.

Weather boundaries located in regions A, B, and C benefit from installation of small hybrid GHP systems because of frequent annual use of the AE unit. When outside temperatures reach the AE setpoint of 10 °C or less, cool air is allowed to flow into the shelter reducing the cooling demand in the GHP system; thus decreasing the BHE field installation size.

In contrast, warmer regions (D and E) may not reach the AE setpoint temperature as often as cooler climatic regions. Therefore, a higher cooling demand is placed in the GHP system requiring large BHE field installations in regions D and E. In this study, the AE setpoint temperature of 10 °C is too low for application in regions with warm climates. Several AE setpoint temperatures are explored for case 2 in section 4.4, and the TEEP sensitivity is analyzed and compared nationwide.

From figures 4.16 and 4.17, regions A, B, and C may require a total BHE length in the range of 100 – 110 m, 130 – 210 m, and 180 – 460 m, respectively. Regions D and E may require a total BHE length in the range of 250 – 900 m and 600 – 1,080 m, respectively. Small hybrid GHP systems are located in high latitude U.S. states, including Maine, New Hampshire, and Minnesota, among others. Large hybrid GHP systems are located in states that have high cooling loads, including parts of Florida, Louisiana, Texas, and Arizona, among others.

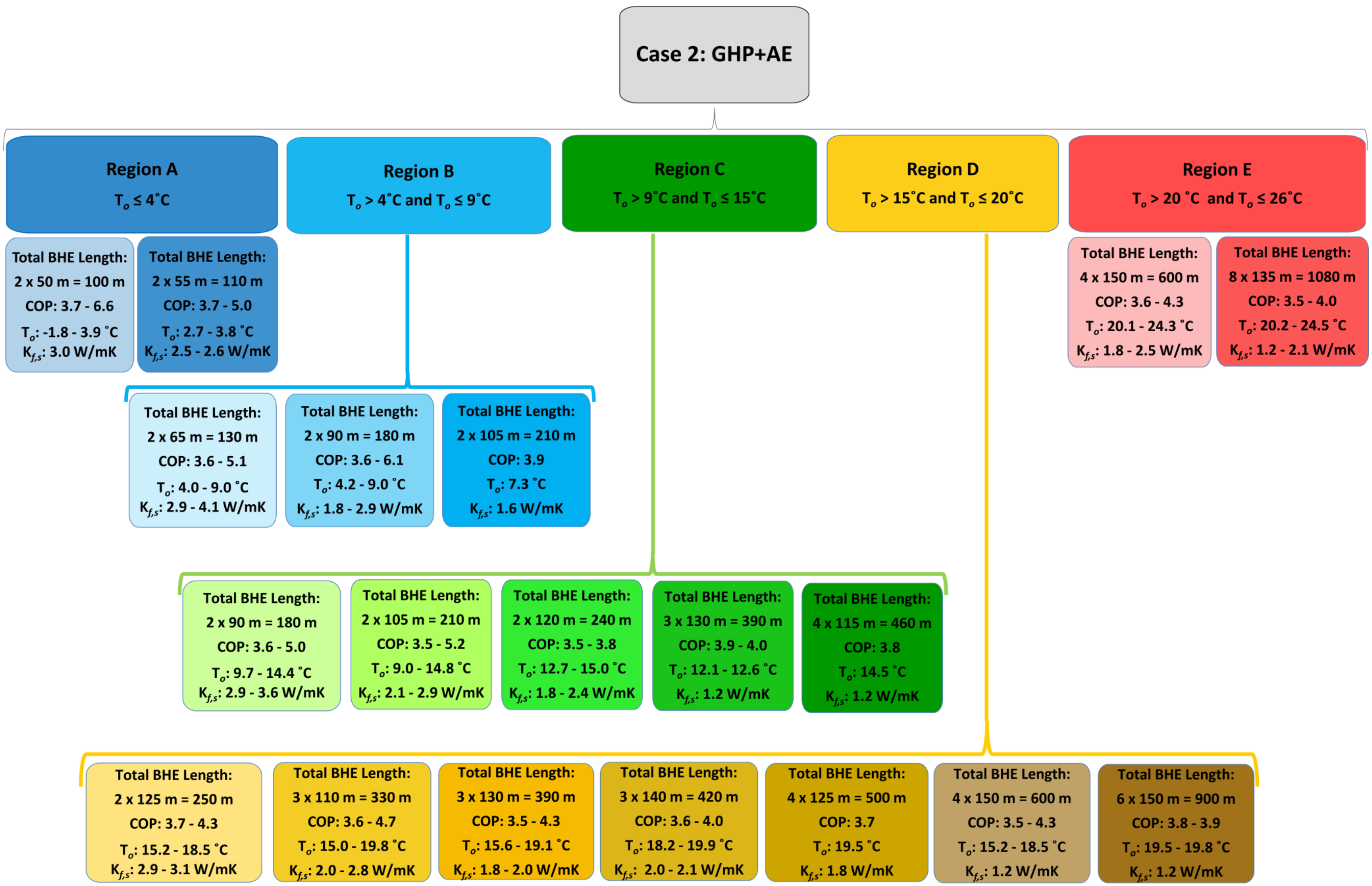

Figure 4.16 - Summary of the technical performance for 269 weather boundaries simulated in the five climatic subdivisions for case 2: GHP + AE.

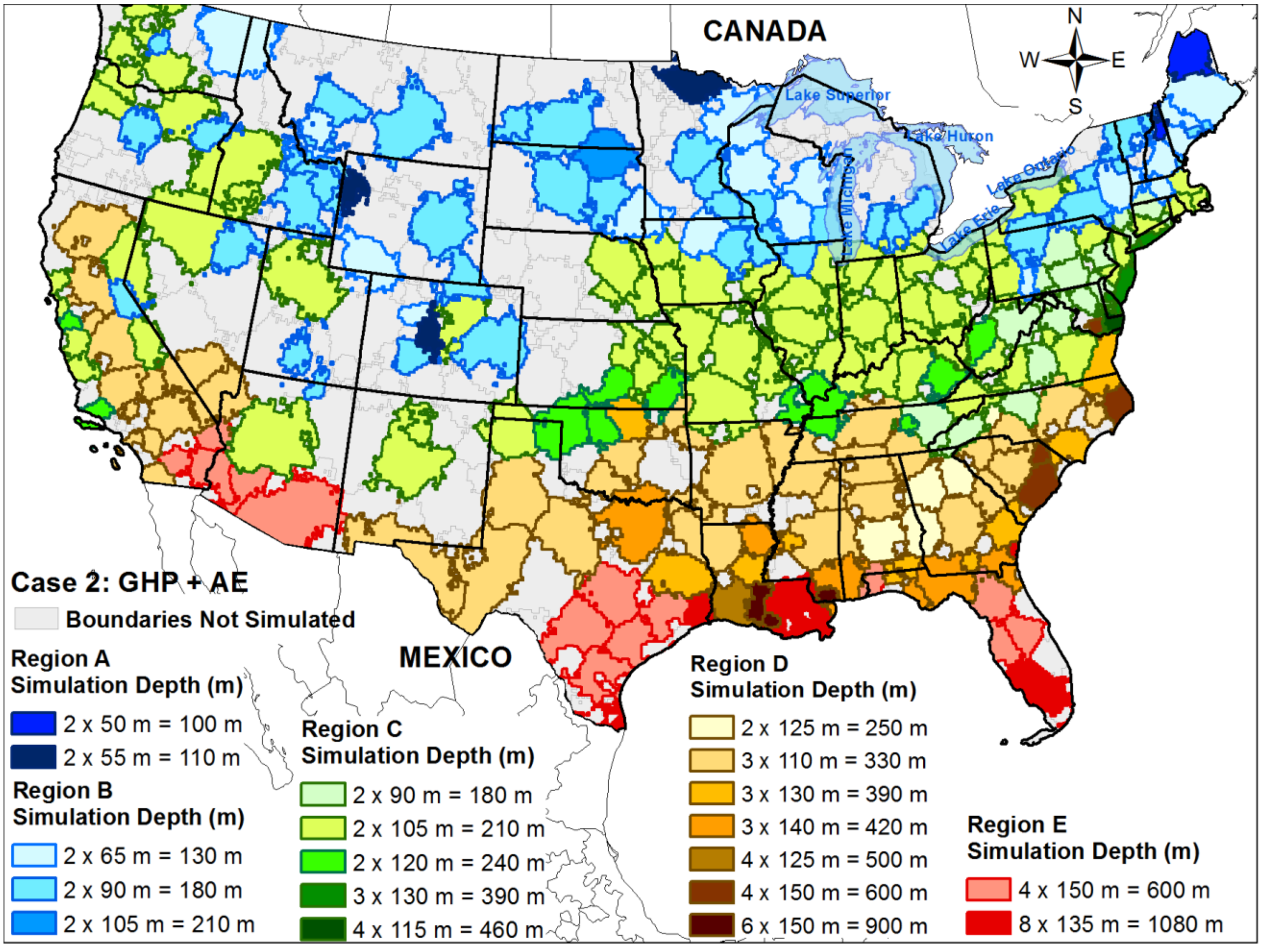

Figure 4.17 - Map of the total borehole (BHE) length (m) for 269 simulated weather boundaries in five climatic subdivisions for case 2: GHP + AE.

The TEEP performance for weather boundaries simulated in case 2 are provided in Table 4.10 based on the subdivisions presented in Figure 4.16. Similarly to case 1, the CAP costs increase with increasing total BHE length for case 2. In regions A and B, the CAP costs are the lowest and range from \$20,700 - \$25,500. In regions C and D, CAP costs range from \$24,800 - \$38,500 and \$28,300 - \$60,100, respectively. The highest CAP costs are estimated in areas of high cooling loads (Region E), which can range from \$44,800 - \$68,900. In case 2, the CAP costs for regions A, B, and C are lower than case 1 because the use of the AEs result in small

BHE field installations. However, in regions D and E the use of AE does not result in a decrease of the BHE field installation size, but does add unit capital expenditure to the system.

Table 4.10 - Summary of the technical, economic, and environmental performance (TEEP) for 269 weather boundaries simulated in five climatic subdivisions for case 2: GHP + AE.

Region	Total BHE Length (m)	Total Cost of Ownership (TCO) ($1,000)	Capital (CAP) Cost ($1,000)	Lifetime O&M (LOM) Cost ($1,000)	Lifetime Electric Consumption (LEC) (MWhe)	Lifetime CO_{2e} Emissions (LCO_2e) (tons)	Lifetime Average COP	Simulated Boundaries
A	2 x 50 m = 100 m	29.2 - 38.5	21.3	8.0 - 17.3	20.4 - 126.8	5.9 - 37.0	3.7 - 6.6	2
A	2 x 55 m = 110 m	32.0 - 36.3	20.7 - 21.3	10.8 - 15.6	66.2 - 141.1	51.4 - 91.8	3.7 - 5.0	3
B	2 x 65 m = 130 m	33.4 - 49.3	21.5 - 22.8	11.2 - 26.5	84.8 - 190.5	25.8 - 114.7	3.6 - 5.1	19
B	2 x 90 m = 180 m	33.8 - 50.8	23.7 - 25.5	9.2 - 25.3	55.7 - 172.7	16.9 - 141.1	3.6 - 6.1	43
B	2 x 105 m = 210 m	41.7	24.9	16.7	168.6	109.7	3.9	1
C	2 x 90 m = 180 m	40.5 - 55.7	24.8 - 25.5	15.7 - 30.2	142.8 - 256.2	30.1 - 134.3	3.6 - 5.0	18
C	2 x 105 m = 210 m	39.2 - 66.5	25.0 - 27.0	13.1 - 40.4	124.2 - 324.7	27.0 - 193.2	3.5 - 5.2	79
C	2 x 120 m = 240 m	47.7 - 67.2	26.2 - 27.8	20.9 - 39.7	233.5 - 318.2	90.1 - 193.1	3.5 - 3.8	10
C	3 x 130 m = 390 m	58.3 - 65.1	35.6 - 36.5	22.7 - 28.6	199.8 - 204.1	78.3 - 111.0	3.9 - 4.0	4
C	4 x 115 m = 460 m	62.1	38.5	23.6	245.0	96.0	3.8	1
D	2 x 125 m = 250 m	48.4 - 57.4	28.3	20.1 - 29.2	221.0 - 302.1	114.5 - 158.3	3.7 - 4.3	5
D	3 x 110 m = 330 m	50.2 - 76.2	30.8 - 32.2	18.0 - 44.3	204.7 - 361.9	68.7 - 179.3	3.6 - 4.7	40
D	3 x 130 m = 390 m	53.7 - 65.7	33.9 - 35.1	19.9 - 30.6	219.5 - 328.3	94.2 - 181.4	3.5 - 4.3	10
D	3 x 140 m = 420 m	58.5 - 66.7	36.6	21.9 - 30.2	273.5 - 335.0	137.2 - 173.7	3.6 - 4.0	6
D	4 x 125 m = 500 m	66.1	40.5	25.6	318.2	187.9	3.7	1
D	4 x 150 m = 600 m	67.1 - 74.7	45.4	21.7 - 29.3	224.4 - 324.2	91.7 - 138.1	3.5 - 4.3	4
D	6 x 150 m = 900 m	85.3 - 86.5	60.1	25.2 - 26.4	296.9 - 315.8	149.0 - 186.5	3.8 - 3.9	3
E	4 x 150 m = 600 m	68.3 - 83.9	44.8 - 45.4	22.9 - 39.1	272.3 - 357.2	127.9 - 183.2	3.6 - 4.3	14
E	8 x 135 m = 1080 m	93.8 - 100.7	68.9	24.9 - 31.8	307.1 - 365.4	147.3 - 190.3	3.5 - 4.0	6

In case 2, the LEC, LOM costs, and LCO_2e emissions increase with increasing total BHE length. Compared to case 1, the LEC and LOM costs in cool regions (A and B) are significantly lower for case 2 because the GHP system is not in operation when the AE activates. For Region A, the LEC and LOM costs range from 20.4 – 141.1 MWhe and $8,000 – $17,300, respectively. For Region B, the LEC and LOM costs range from 55.7 – 190.5 MWhe and $9,200 – 26,500, respectively. For Region C, the LEC and LOM costs range from 124.2 – 324.7 MWhe and $13,100 - $40,400, respectively. For Region D, the LEC and LOM costs range from 204.7 – 361.9 MWhe and $18,000 - $44,300, respectively. For Region E, the LEC and LOM costs range from 272.3 – 365.4 MWhe and $22,900 – $39,100, respectively.

In Figure 4.18, the TCO is provided for each simulated weather boundary based on climatic and total BHE length subdivisions outlined in Table 4.10. TCO for regions A and B ranges from \$29,200 - \$38,500 and \$33,400 - \$50,800, respectively. For regions C and D, the TCO ranges from \$39,200 - \$67,200 and \$48,400 - \$86,500, respectively. The highest TCO is observed in Region E, and ranges from \$68,300 - \$100,700. All regions, except Region E, in case 2 result in a lower TCO when compared to case 1. The current AE setpoint temperature of 10 °C does not provide any technical, economic, or environmental benefits for regions with T_o > 20 °C.

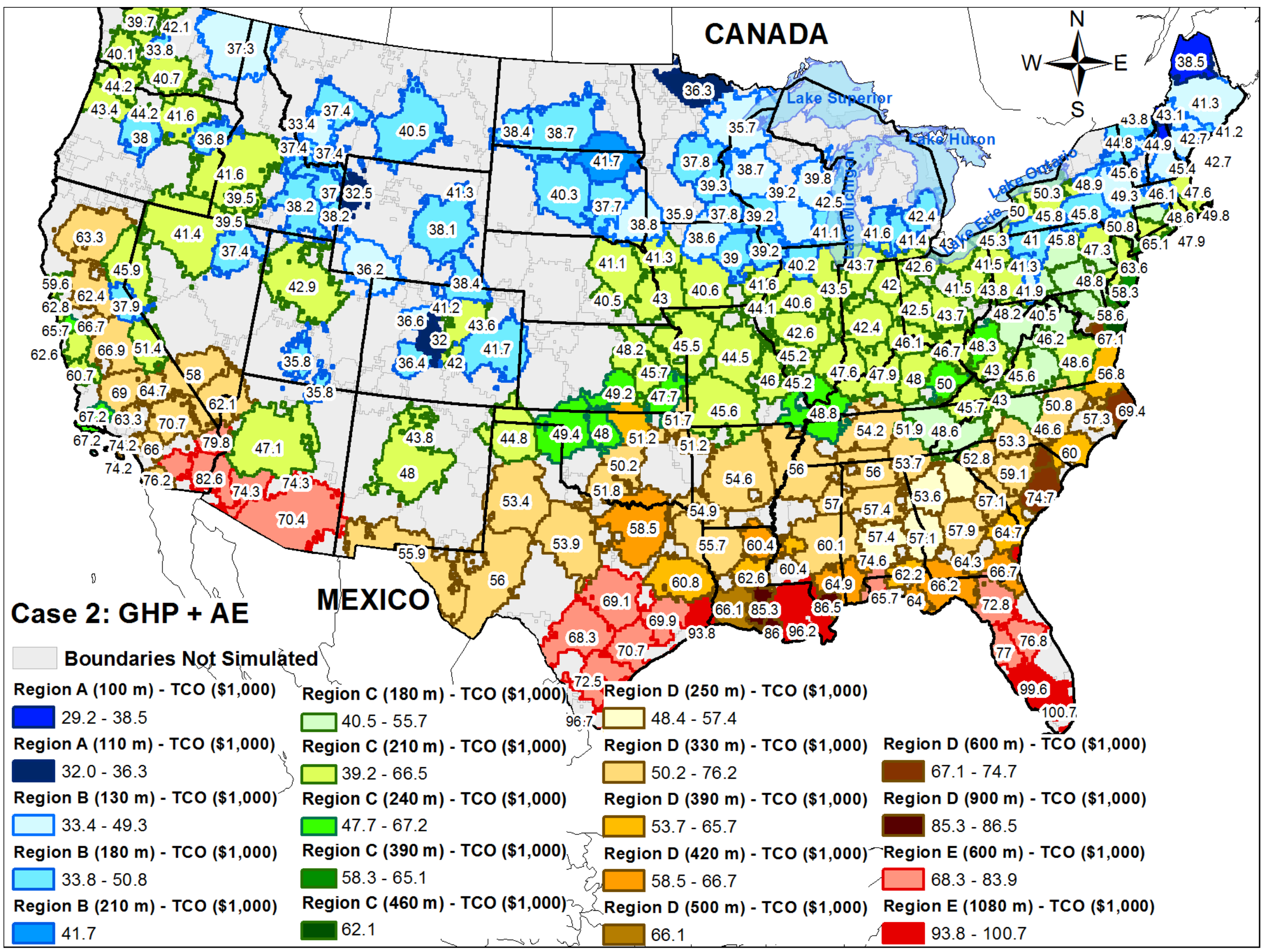

Figure 4.18 - Map of the total cost of ownership (TCO) for 269 simulated weather boundaries based on climatic and total BHE length subdivision for case 2: GHP + AE.

For the remaining 276 TMY3 weather boundaries not simulated in Figure 4.16, boundaries were classified according to Figure 4.19. In Region A, weather boundaries corresponding to $T_0 \leq 4$ °C and $K_{f,s}$ of 2.4 – 4.1 W/m·K were estimated to have a total BHE length of 110 m. In Region B with $T_o > 4$ °C and ≤ 9 °C and $K_{f,s} < 2.0$ – 4.1 W/m·K, the total BHE length ranges from 130 – 210 m. In Region C with $T_o > 9$ °C and ≤ 15 °C and $K_{f,s} < 2.0$ – 4.1 W/m·K, the total BHE length ranges from 180 – 460 m. In Region D with $T_o > 15$ °C and ≤ 20 °C and $K_{f,s} <1.8$ – 4.1 W/m·K, the total BHE length ranges from 250 – 900 m. In Region E with $T_o > 20$ °C and ≤ 26 °C and $K_{f,s} <2.1$ – 4.1 W/m·K, the total BHE length ranges from 600 – 1080 m.

Nationwide generalizations based on Figure 4.19 were made to summarize the TEEP of case 2 from regional climatic subdivisions and thermal soil/rock properties. In Figure 4.20, summary results of the TCO, CAP and LOM costs, LEC, LCO_2e, and lifetime average COP are provided. Compared to case 1, regions A, B, and C in case 2 result in a decrease of costs, LEC, and LCO_2e emissions because of reductions in BHE field installations and electricity consumption from employing AE units. As expected, Region A results in the highest COP and lowest overall costs. On the other hand, installing hybrid GHP systems in warm climates result in higher overall costs, as observed in Region E.

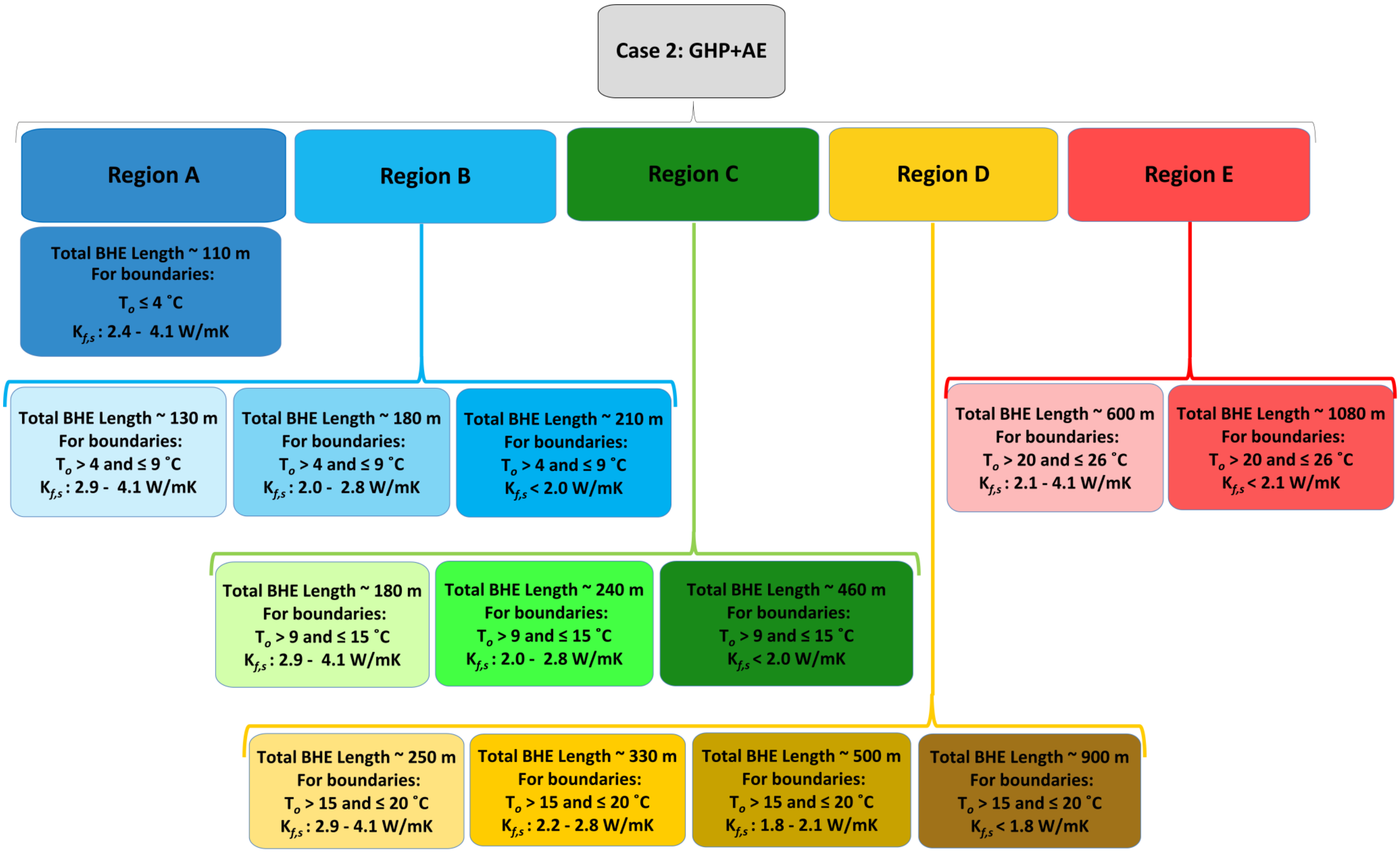

Figure 4.19 - Nationwide generalizations used to estimate the technical, economic, and environmental performance (TEEP) of all 545 TMY3 weather boundaries based on simulation results of the 269 weather boundaries presented in Figure 4.16 for case 2: GHP + AE.

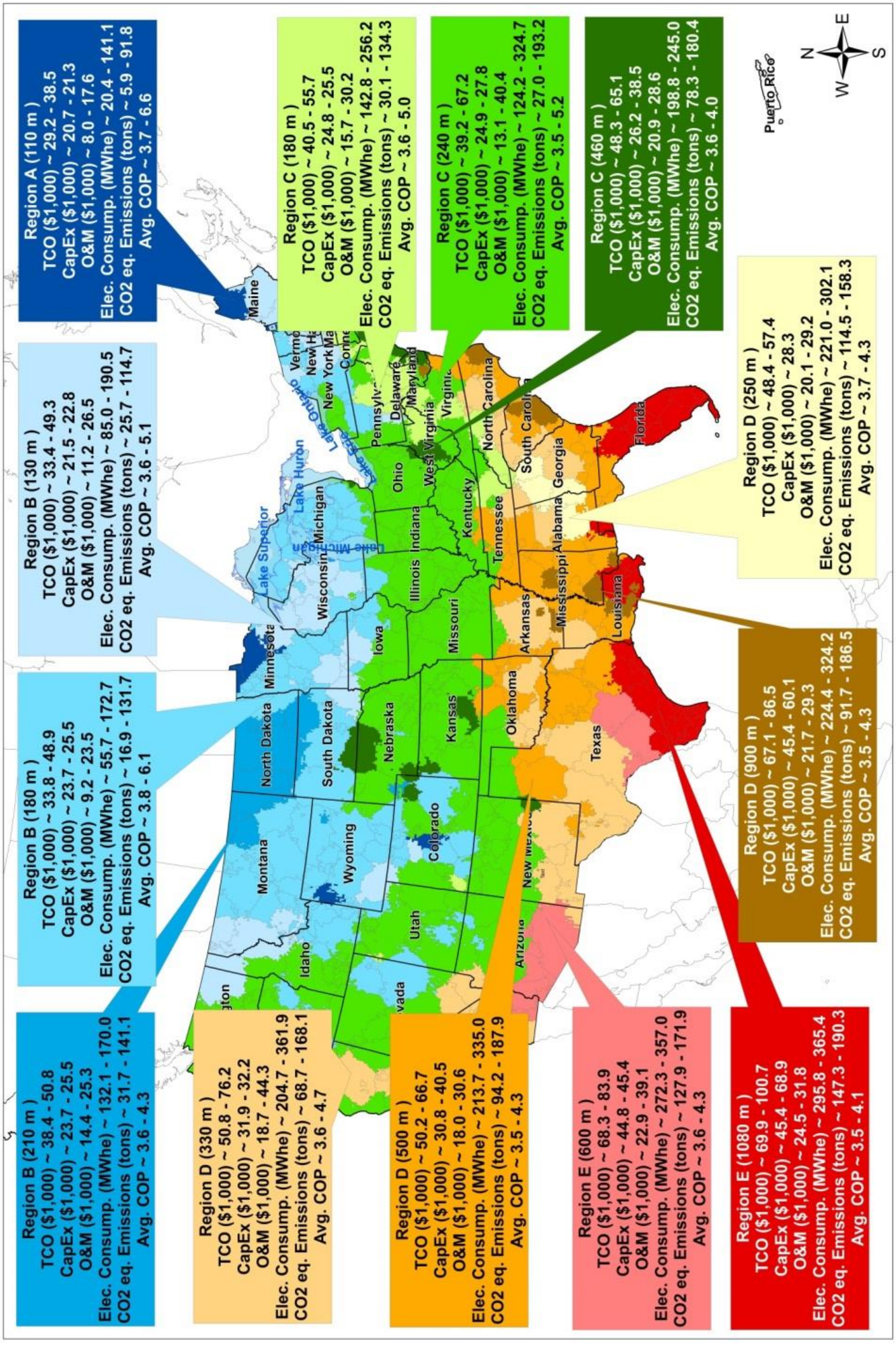

Figure 4.20 - Nationwide technical, economic, and environmental performance (TEEP) results by climatic region from generalizations presented in Figure 4.19 for case 2: GHP + AE.

4.3.3: Case 3: Geothermal Heat Pump (GHP) + Dry-Cooler (DC)

The TEEP simulations for case 3 were performed similarly to case 1 (section 4.3.1) and case 2 (section 4.3.2). From figures 4.21 and 4.22, a summary of the technical performance, including total BHE length and COP, for the 269 weather boundaries simulated in case 3 is presented. For all climatic regions in case 3, the estimated total BHE lengths are the lowest of all three GHP cases because the DC unit is used during a significant amount of time during the year.

The DC temperature setpoint for each weather boundary was selected at 5 °C above the mean annual surface temperature of the area. At times when the hourly surface temperature of the simulated boundary is at or below the DC setpoint, the circulating fluid in the shelter heat pump units bypasses the BHE field and is cooled only by the DC (Beckers, 2016; Williams, 2016).

From figures 4.21 and 4.22, regions A, B, C, and D may require a total BHE length in the range of 70 – 80 m, 90 – 110 m, 110 – 270 m, and 180 – 520 m, respectively. Region E may require a total BHE length of up to 520 m. Comparing the total BHE length for case 1 (GHP-only) and case 3, regions A, B, and C for case 3 report decreases in the total BHE length in the range of 50 – 60%. In case 3, the decrease in the total BHE length for regions D and E ranges from 40 – 50% when compared to case 1.

Comparing case 2 (GHP + AE) and case 3, the total BHE length for regions A, B, and C for case 3 decreases by around 27 – 47%. The highest decrease of over 50% in the total BHE length from case 2 to case 3 occurs in Region E. Region E in case 2 does not benefit from an AE unit because the setpoint temperature of 10 °C is too low for application in regions with warm climates. On the contrary, coupling the GHP system with DC units in all climatic regions results in small BHE field installations because the DC unit actively cools the shelter while allowing the field to thermally “recharge” (Beckers, 2016).

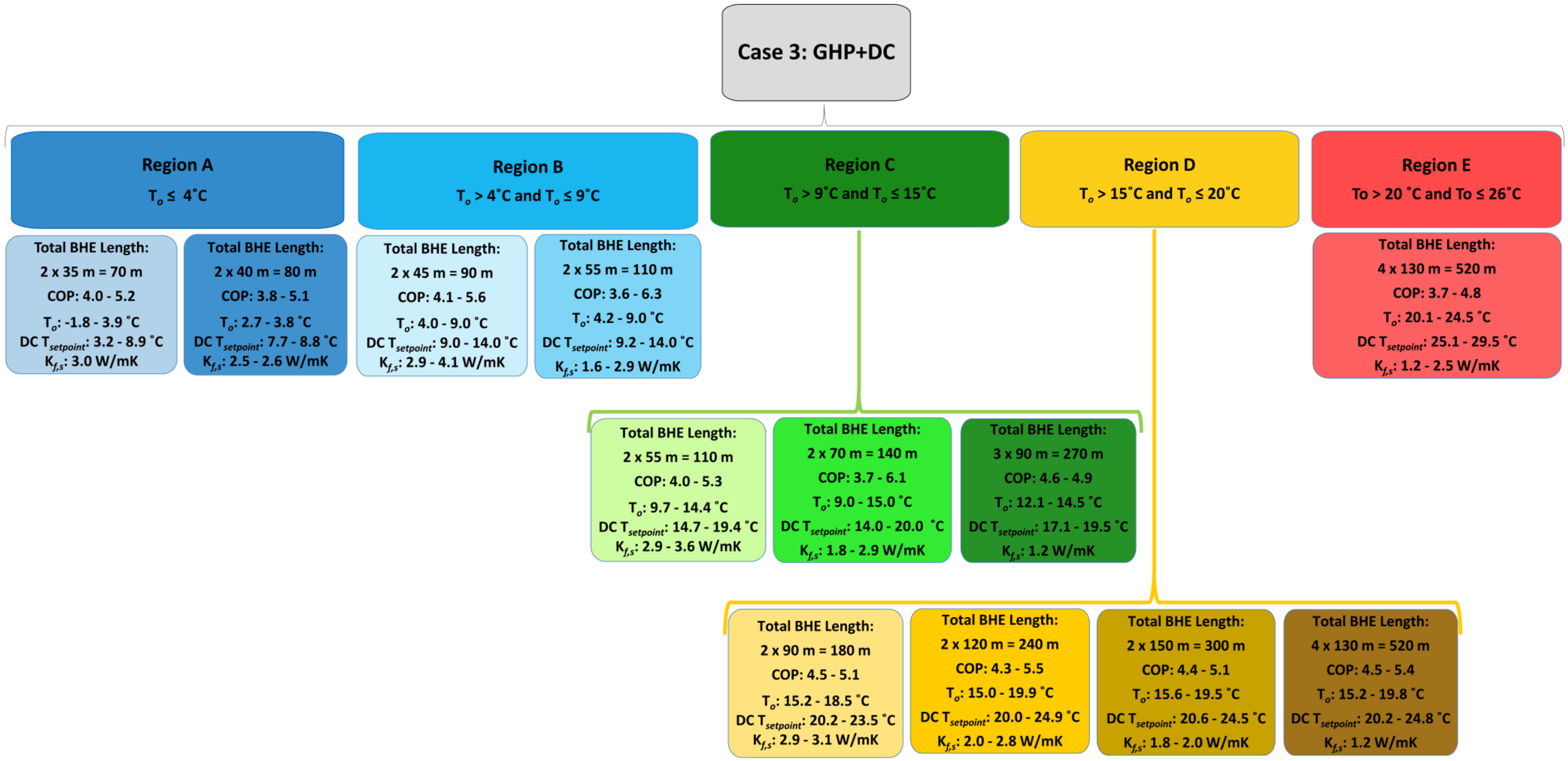

Figure 4.21 - Summary of the technical performance for 269 weather boundaries simulated in the five climatic subdivisions for case 3: GHP + DC.

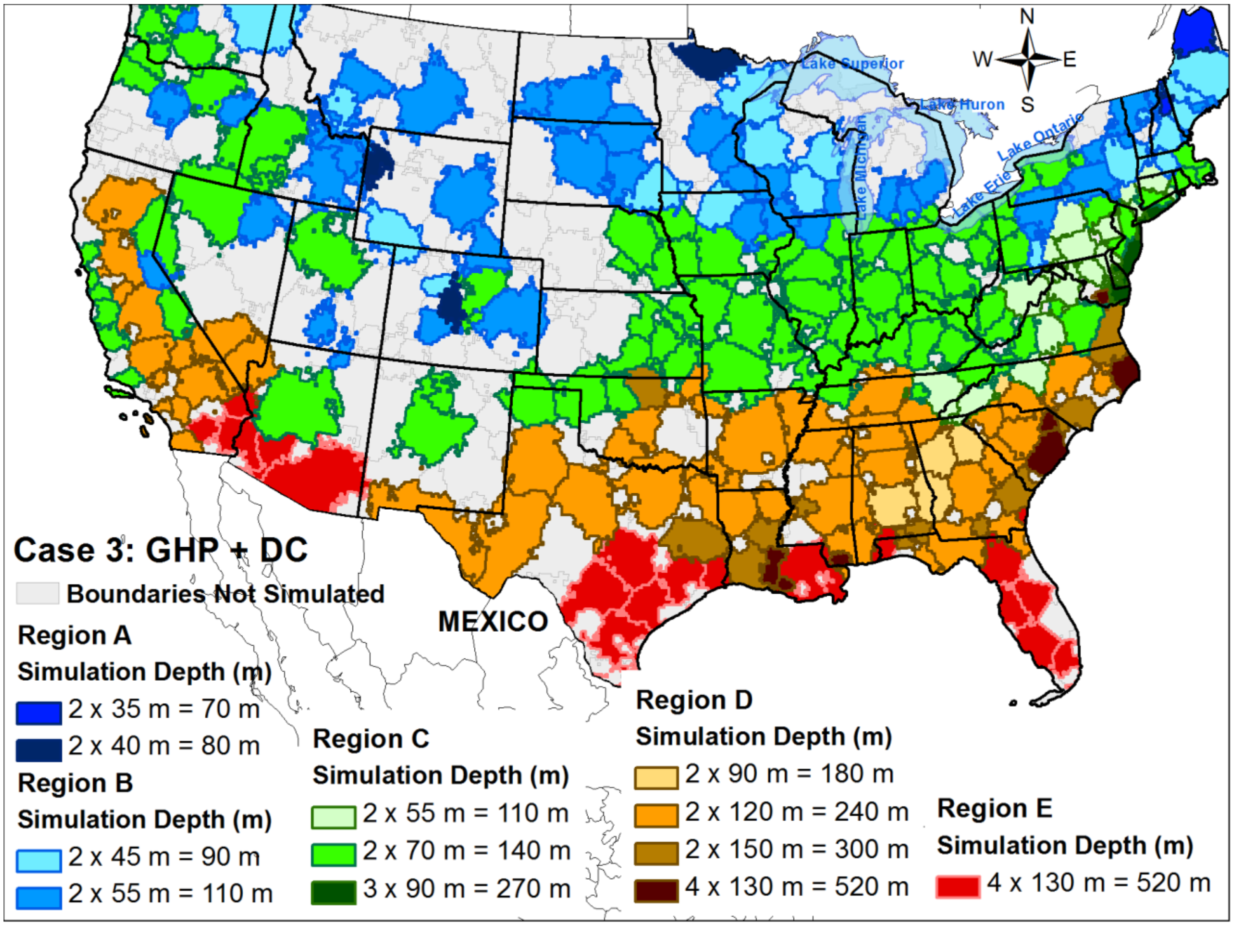

Figure 4.22 - Map of the total borehole (BHE) length (m) for 269 simulated weather boundaries in five climatic subdivisions for case 3: GHP + DC.

The TEEP performance of weather boundaries simulated in case 3 are provided in Table 4.11 based on the subdivisions presented in Figure 4.21. Similarly to cases 1 and 2, the CAP costs increase with increasing total BHE length for case 3. In regions A and B, the CAP costs are the lowest and range from \$19,400 - \$21,800. In regions C and D, CAP costs range from \$21,400 - \$30,200 and \$24,800 - \$41,500, respectively. In Region E, CAP costs are over \$41,000. Overall, the capital costs for case 3 are lower than for cases 1 and 2 because the total borehole lengths are smaller in all climatic regions.

Table 4.11 - Summary of the technical, economic, and environmental performance (TEEP) for 269 weather boundaries simulated in five climatic subdivisions for case 3: GHP + DC.

Region	Total BHE Length (m)	Total Cost of Ownership (TCO) ($1,000)	Capital (CAP) Cost ($1,000)	Lifetime O&M (LOM) Cost ($1,000)	Lifetime Electric Consumption (LEC) (MWhe)	Lifetime CO_{2e} Emissions (LCO_2e) (tons)	Lifetime Average COP	Simulated Boundaries
A	2 x 35 m = 70 m	53.5 - 57.1	19.7	33.8 - 37.4	309.1 - 385.0	90.2 - 112.4	4.0 - 5.2	2
A	2 x 40 m = 80 m	42.9 - 49.5	19.4 - 19.8	23.0 - 30.1	317.8 - 393.9	193.7 - 264.3	3.8 - 5.1	3
B	2 x 45 m = 90 m	41.9 - 65.2	19.8 - 20.7	21.6 - 44.5	300.6 - 381.2	90.6 - 266.6	4.1 - 5.6	19
B	2 x 55 m = 110 m	40.4 - 70.1	20.7 - 21.8	19.1 - 48.3	278.8 - 421.9	68.1 - 322.4	3.6 - 6.3	44
C	2 x 55 m = 110 m	46.4 - 66.3	21.4 - 21.8	25.0 - 44.4	315.4 - 400.8	62.4 - 209.2	4.0 - 5.3	18
C	2 x 70 m = 140 m	42.6 - 64.0	22.0 - 23.4	19.9 - 40.6	296.3 - 421.7	59.7 - 313.6	3.7 - 6.1	89
C	3 x 90 m = 270 m	58.1 - 71.2	29.2 - 30.2	28.9 - 41.0	333.7 - 356.2	130.7 - 184.9	4.6 - 4.9	5
D	2 x 90 m = 180 m	49.2 - 56.7	24.8	24.3 - 32.0	331.3 - 371.6	171.6 - 197.3	4.5 - 5.1	5
D	2 x 120 m = 240 m	49.3 - 71.2	26.7 - 27.8	21.5 - 43.7	317.2 - 388.2	96.2 - 251.4	4.3 - 5.5	46
D	2 x 150 m = 300 m	53.4 - 61.9	29.7 - 30.7	23.7 - 31.2	324.5 - 378.0	133.4 - 241.3	4.4 - 5.1	11
D	4 x 130 m = 520 m	66.6 - 70.6	41.5	25.1 - 29.1	316.5 - 377.4	129.4 - 222.9	4.5 - 5.4	7
E	4 x 130 m = 520 m	66.4 - 84.3	41.0 - 41.5	24.9 - 43.3	353.4 - 468.9	154.9 - 240.5	3.7 - 4.8	20

The LEC and LOM costs for case 3 are comparable and at times higher than those for case 1, and considerably higher than those for case 2. The GHP + DC configuration is expected to consume more electricity during the lifetime of the system because the DC is used significantly throughout the year for all climatic regions. Even though case 3 results in smaller BHE field installations compared to cases 1 and 2, the operating costs for case 3 are the highest of all GHP configurations.

For Region A, the LEC and LOM costs range from 309.1 – 393.9 MWhe and $23,000 – $37,400, respectively. For Region B, the LEC and LOM costs range from 278.8 – 421.9 MWhe and $19,100 – 48,300, respectively. For Region C, the LEC and LOM costs range from 296.3 – 421.7 MWhe and $19,900 - $44,400, respectively. For Region D, the LEC and LOM costs range from 316.5 – 388.2 MWhe and $21,500 - $43,700, respectively. For Region E, the LEC and LOM costs range from 353.4 – 468.9 MWhe and $24,900 – $43,300, respectively.

In Figure 4.23, the TCO is provided for each simulated weather boundary based on climatic and total BHE length subdivisions outline in Table 4.11. The TCO for regions A and B ranges from \$42,900 - \$57,100 and \$40,400 - \$70,100, respectively. For regions C and D, the TCO ranges from \$42,600 - \$71,200 and \$49,200 - \$71,200, respectively. The highest TCO is observed in Region E and ranges from \$66,400 - \$84,300. The TCO for case 3 in cooler regions (regions A and B) is comparable to that of case 1 (GHP-only), but significantly higher than case 2 (GHP + AE). For warmer regions (Region E), the TCO for case 3 is significantly lower than both cases 1 and 2 because the use of a DC allows for smaller BHE field installations in all climatic regions.

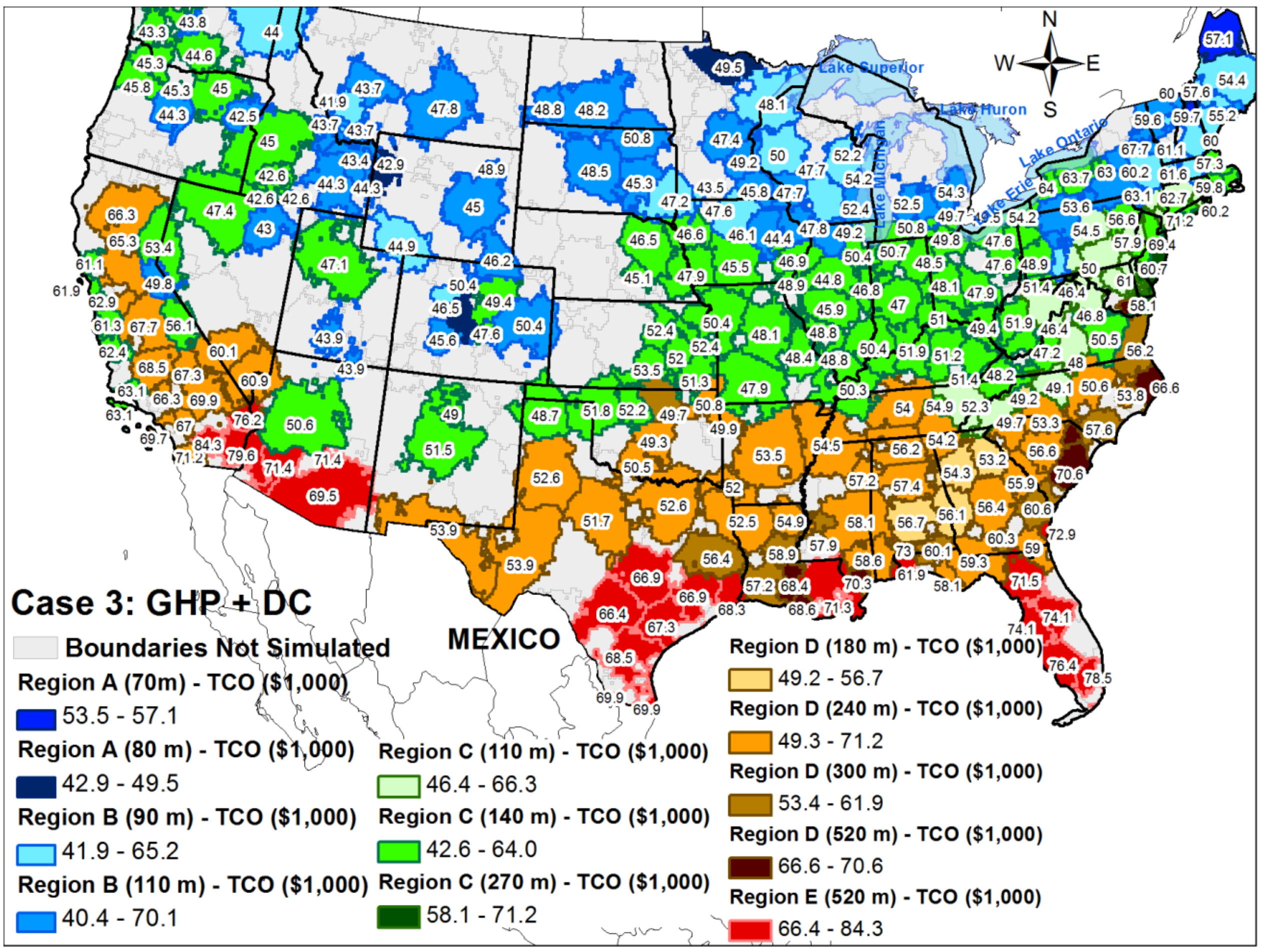

Figure 4.23 - Map of the total cost of ownership (TCO) for 269 simulated weather boundaries based on climatic and total BHE length subdivision for case 3: GHP + DC.

Similar to cases 1 and 2, nationwide TEEP estimates were made for the remaining 276 TMY weather boundaries not simulated in Figure 4.21. From Figure 4.24, weather boundaries in Region A corresponding to $T_0 \leq 4$ °C, $K_{f,s}$ of 2.4 – 4.1 W/m·K, and DC setpoint temperature ($T_{setpoint}$) of 3 – 9 °C were estimated to have a total BHE length of 80 m. In Region B with $T_o > 4$ °C and ≤ 9 °C, $K_{f,s} < 2.9$ – 4.1 W/m·K, and DC $T_{setpoint}$ of 9 – 14 °C , the total BHE length ranges from 90 – 110 m. In Region C with $T_o > 9$ °C and ≤ 15 °C, $K_{f,s} < 2.0$ – 4.1 W/m·K, and DC $T_{setpoint}$ of 14 – 20 °C, the total BHE length ranges from 110 – 270 m. In Region D with $T_o > 15$ °C and ≤ 20 °C, $K_{f,s} < 1.8$ – 4.1 W/m·K, and DC $T_{setpoint}$ of 20 – 25 °C , the total BHE length ranges from 180 – 520 m. In Region E with $T_o > 20$ °C and ≤ 26 °C, $K_{f,s}$ 1.2 – 4.1 W/m·K, and DC $T_{setpoint}$ of 25 – 30 °C , the total BHE length is up to 520 m.

Nationwide generalizations based on Figure 4.24 were made to summarize the TEEP of case 3 from regional climatic subdivisions and thermal soil/rock properties. Nationwide summary results of TCO, CAP and LOM costs, LEC, LCO_2e, and lifetime average COP are provided in Figure 4.25. Compared to cases 1 and 2, the capital costs for case 3 in all climatic regions are lower because DC units result in smaller total BHE length installations. However, operating costs of case 3 surpass the costs of cases 1 and 2. The DC unit consumes more electricity during the lifetime of the system because it is expected to be used during a significant amount of time during the year. The TCO for case 3 in cool regions (regions A and B) is comparable to that of case 1 (GHP-only), but significantly higher than case 2 (GHP + AE). For warm regions (Region E), the TCO for case 3 is significantly lower than both cases 1 and 2 because the use of a DC allows for smaller BHE field installations.

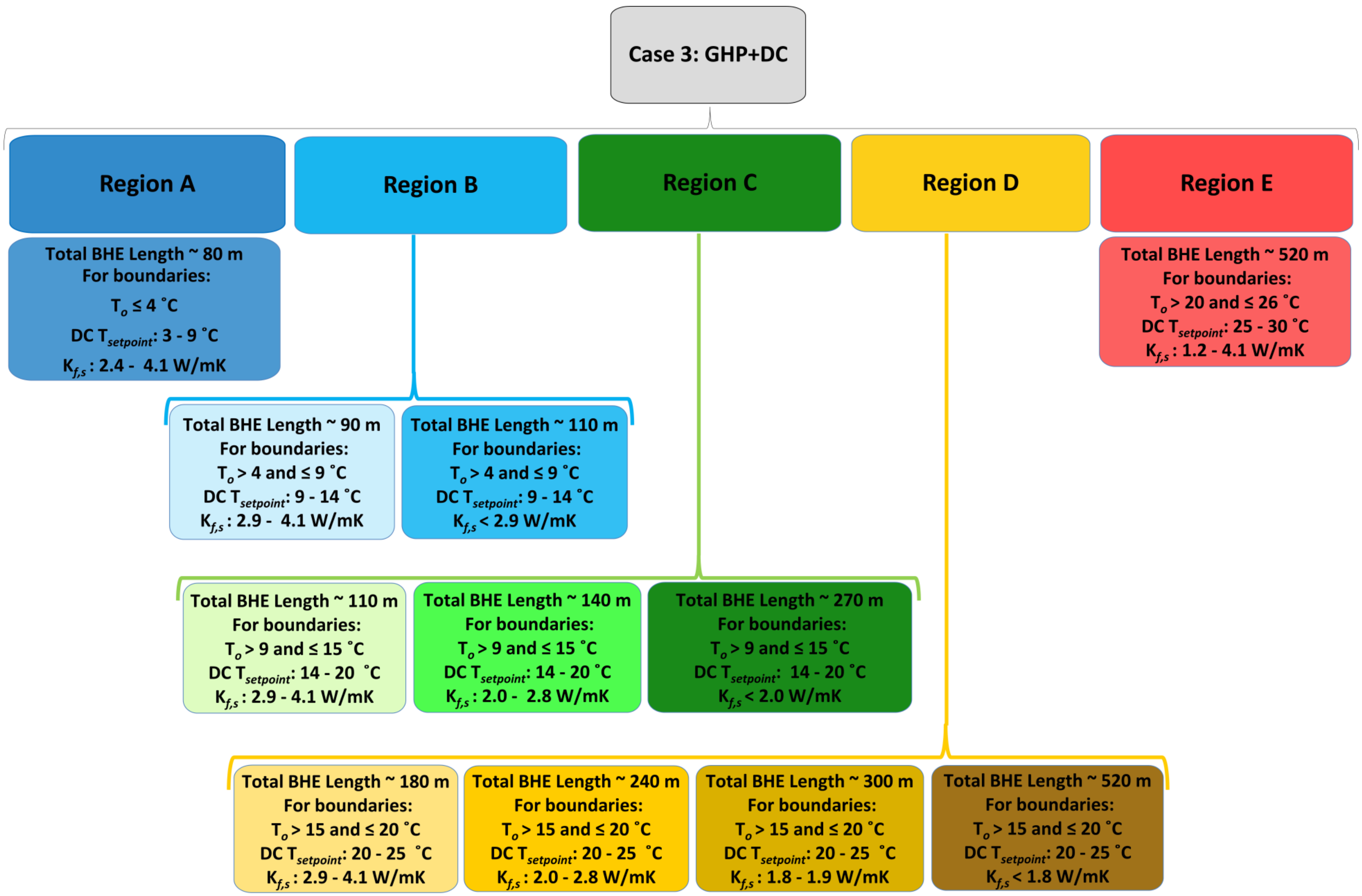

Figure 4.24 - Nationwide generalizations used to estimate the technical, economic, and environmental performance (TEEP) of all 545 TMY3 weather boundaries based on simulation results of the 269 weather boundaries presented in Figure 4.21 for case 3: GHP + DC.

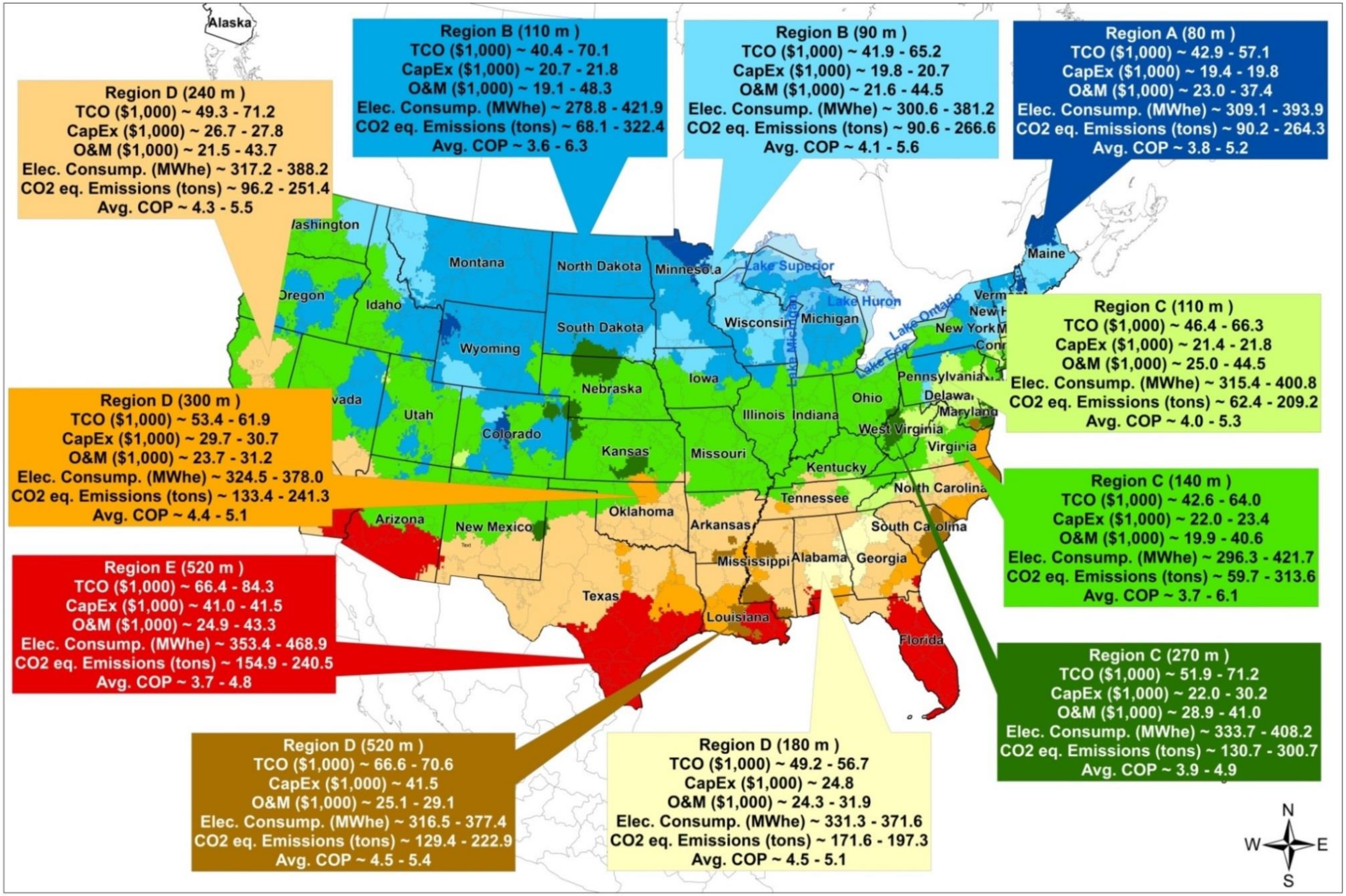

Figure 4.25 - Nationwide technical, economic, and environmental performance (TEEP) results by climatic region from generalizations presented in Figure 4.24 for case 3: GHP + DC.

4.3.4: Case 4: Air Source Heat Pump (ASHP) – only (BAU)

ASHPs represent the current business-as-usual (BAU) cooling configuration utilized in most cellular tower shelters nationwide. The techno-economic simulation times per weather boundary for cases involving ASHPs (cases 4 and 5) are significantly shorter than for cases involving GHPs (cases 1 – 3). Therefore, all 545 TMY3 weather boundaries were simulated for case 4, and the TEEP results are presented in Table 4.12 and figures 4.26 – 4.27 based on the five climatic regions presented in Figure 4.3 of Section 4.2.2.

Table 4.12 - Summary results of technical, economic, and environmental performance (TEEP) for all 545 weather boundaries simulated in five climatic subdivisions for case 4: ASHP.

Region	Total Cost of Ownership (TCO) ($1,000)	Capital (CAP) Cost ($1,000)	Lifetime O&M (LOM) Cost ($1,000)	Lifetime Electric Consumption (LEC) (MWhe)	Lifetime CO_2e Emissions (LCO_2e) (tons)	Lifetime Average COP	Simulated Boundaries
A	39.5 - 52.2	8.7	30.8 - 43.5	348.0 - 379.8	101.6 - 307.6	3.4 - 3.6	7
B	39.1 - 63.4	8.7	30.4 - 54.6	378.6 - 406.0	71.7 - 337.3	3.3 - 3.4	145
C	39.8 - 65.1	8.7	31.1 - 56.4	402.7 - 442.3	75.3 - 350.5	3.1 - 3.3	221
D	42.6 - 68.0	8.7	33.9 - 59.3	436.3 - 474.1	129.3 - 336.5	2.9 - 3.1	126
E	46.1 - 71.3	8.7	37.4 - 62.6	470.6 - 508.8	141.6 - 341.1	2.8 - 2.9	46

From Table 4.12, the TCO is largely driven by LOM costs, which depend on the regional LEC and statewide electricity rates (see Figure 4.6 in Section 4.2.5). Large variations in the TCO within climatic regions occur because of variations in statewide electricity rates. The CAP costs associated with case 4 are the lowest for all five case studies because no BHE field installation is required, and only the mechanical equipment is considered. The CAP costs include two ASHP units replaced after 10 years of service.

In Figure 4.26, the TCO is provided for each simulated weather boundary based on climatic regions outline in Table 4.12. The TCO for regions A and B ranges from $39,500 - $52,200 and $39,100 - $63,400, respectively. For regions C and D, the TCO ranges from

$39,800 - $65,100 and $42,600 - $68,000, respectively. The highest TCO is observed in Region E and ranges from $46,100 - $71,300.

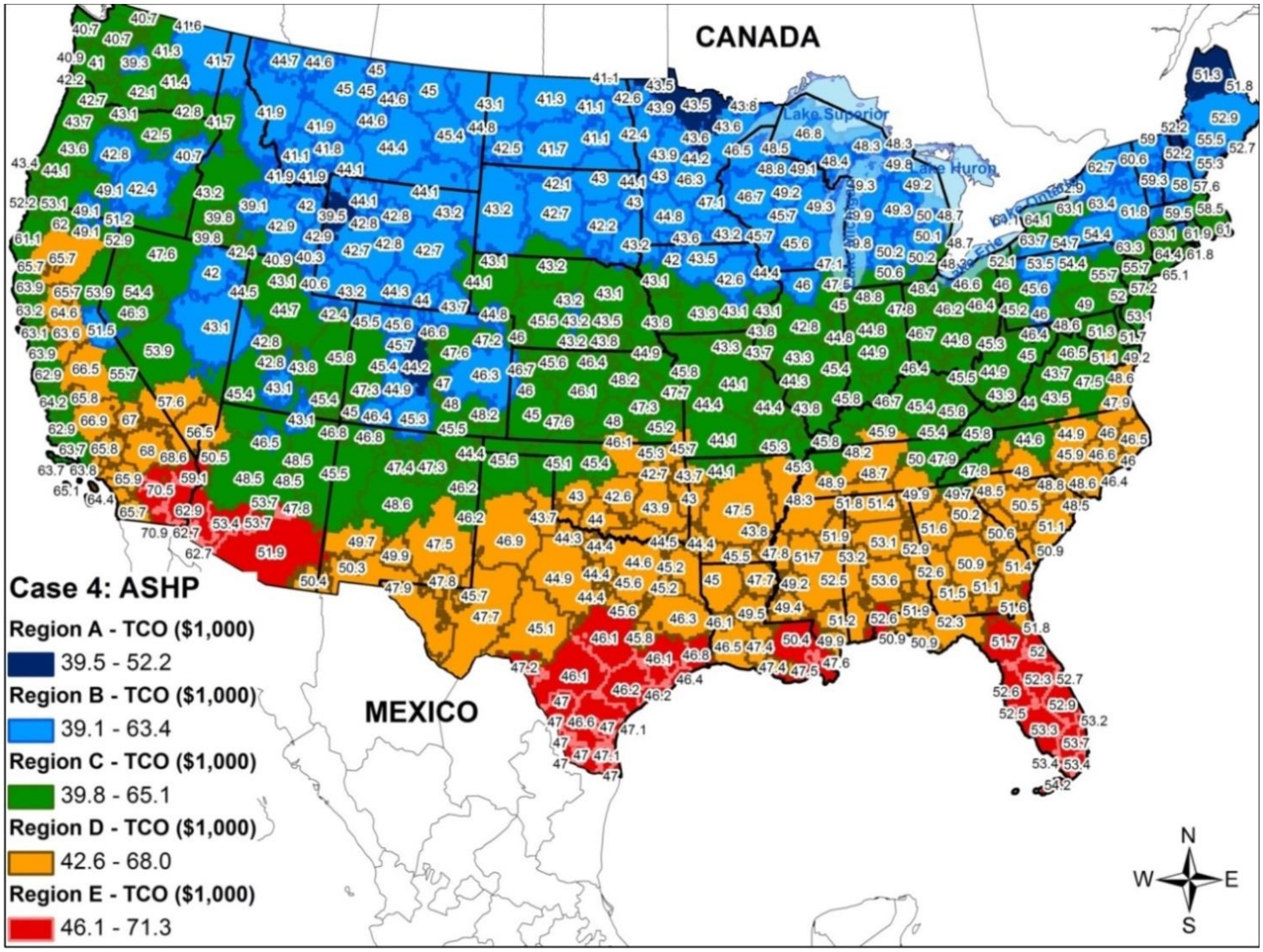

Figure 4.26 -Map of the total cost of ownership (TCO) for all 545 weather boundaries based on climatic subdivisions for case 4: ASHP.

Nationwide summary results of the TCO, CAP and LOM costs, LEC, LCO_2e emissions, and lifetime average COP are provided in Figure 4.27. Cooler regions (A and B) report lower TCO and LOM costs, and warmer regions (C, D and E) report higher costs. In cooling-dominated applications, regions with lower cooling loads (A and B) report higher COP and lower LEC and LCO_2e emissions than regions with higher cooling loads (C, D, and E). Compared to GHP cases, ASHPs result in higher LEC, LCO_2e emissions, and LOM costs for most climatic regions. However, the TCO of ASHPs is lower than most GHP cases because the CAP costs of ASHPs are minimal compared to the CAP costs required for GHP installations.

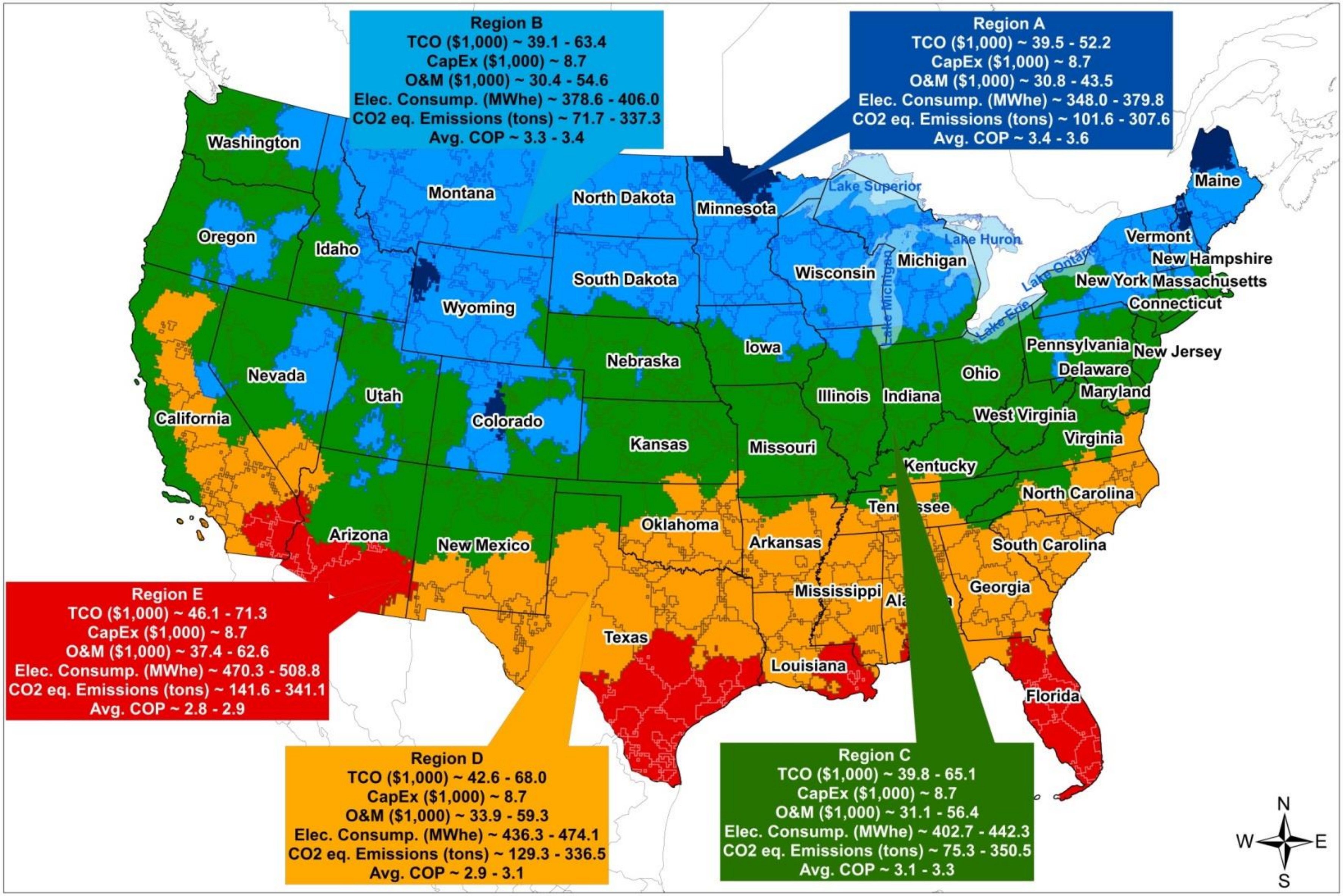

Figure 4.27 - Summary of the technical, economic, and environmental performance (TEEP) of all 545 TMY3 weather boundaries for case 4: ASHP.

4.3.5: Case 5: Air Source Heat Pump (ASHP) + Air Economizer (AE)

Case 5 presents a hybridized option to the current BAU cooling configuration (case 4: ASHP) for cellular tower shelters. All 545 TMY3 weather boundaries were simulated for case 5, and the TEEP results are presented in Table 4.13 and figures 4.28 – 4.29 based on five climatic regions (see Figure 4.3 of Section 4.2.2). Similar to case 2 (GSHP+AE), the AE temperature setpoint for case 5 is 10 °C.

Table 4.13 - Summary results of technical, economic, and environmental performance (TEEP) for all 545 weather boundaries simulated in five climatic subdivisions for case 5: ASHP + AE.

Region	Total Cost of Ownership (TCO) ($1,000)	Capital (CAP) Cost ($1,000)	Lifetime O&M (LOM) Cost ($1,000)	Lifetime Electric Consumption (LEC) (MWhe)	Lifetime CO_2e Emissions (LCO_2e) (tons)	Lifetime Average COP	Simulated Boundaries
A	25.8 - 35.4	9.7	16.1 - 25.7	44.9 - 175.2	13.1 - 114.0	3.0 - 3.2	7
B	27.7 - 46.4	9.7	18.0 - 36.6	110.1 - 235.5	31.4 - 179.2	2.9 - 3.1	145
C	32.7 - 62.9	9.7	23.0 - 53.2	196.0 - 387.7	41.3 - 238.2	2.8 - 3.2	221
D	39.6 - 68.7	9.7	29.9 - 59.0	319.6 - 442.0	98.0 - 256.2	2.8 - 3.0	126
E	46.9 - 73.7	9.7	37.2 - 64.0	413.4 - 508.7	122.5 - 320.2	2.7 - 2.9	46

From Table 4.13, the use of AE units benefit climatic regions A and B the most because cool air flowing into the shelter reduces the load in the ASHP. When the cooling load in the ASHP is reduced, less electricity is consumed, lower CO_2e emissions are released, and lower operating costs result. However, warm climatic regions (C, D, and E) may not reach the AE setpoint temperature as often as cool regions diminishing the benefits of the hybridized ASHP option. The CAP costs of case 5 are slightly higher than case 4 because of the additional AE unit.

In Figure 4.28, the TCO is provided for each simulated weather boundary based on climatic regions outlined in Table 4.13. The TCO for regions A and B ranges from $25,800 - $35,400 and $27,700 - $46,400, respectively. For regions C and D, the TCO ranges from

$32,700 - $62,900 and $39,600 - $68,700, respectively. The highest TCO is observed in Region E and ranges from $46,900 - $73,700.

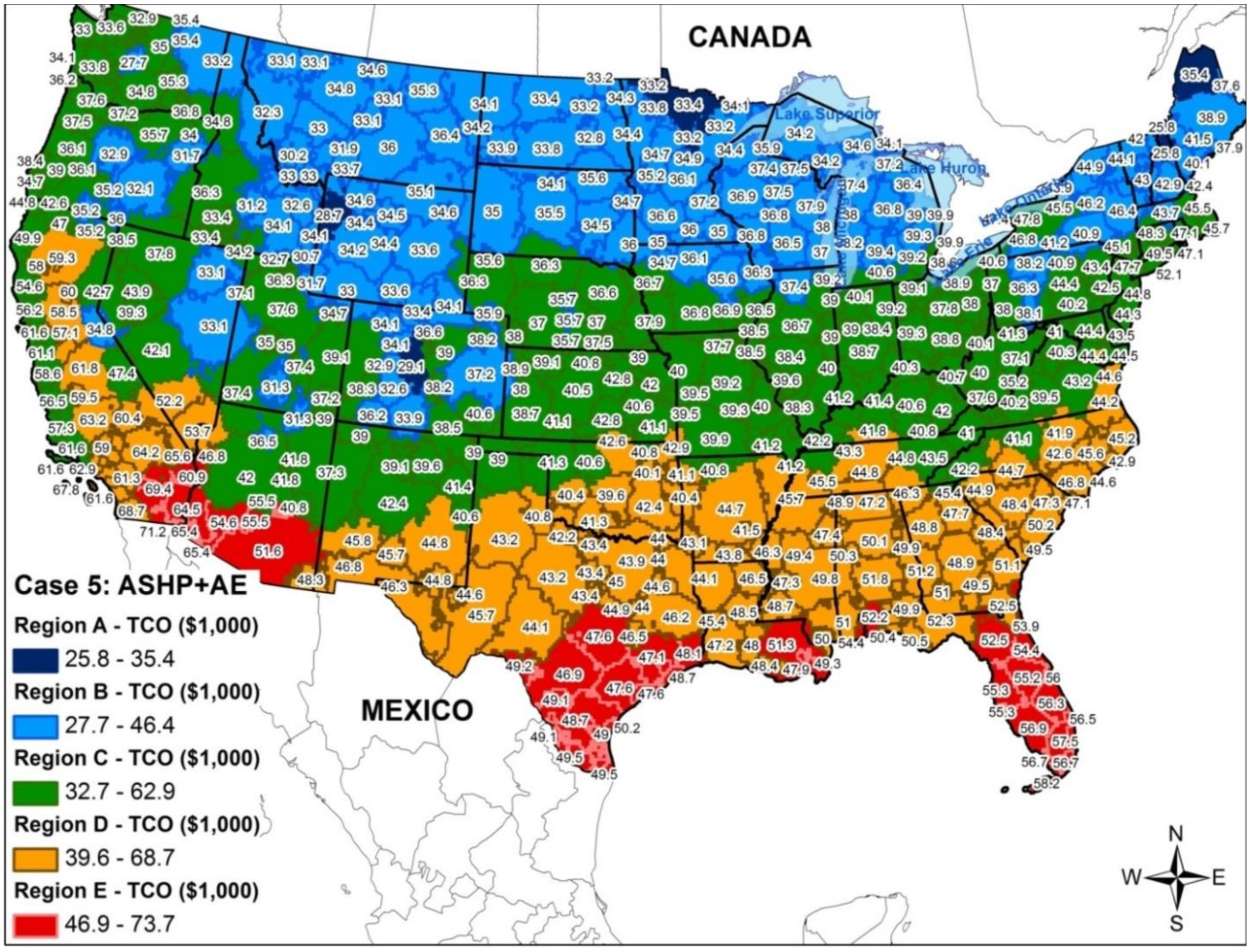

Figure 4.28 -Map of the total cost of ownership (TCO) for all 545 weather boundaries based on climatic subdivisions for case 5: ASHP + AE.

From Figure 4.28, the TCO is significantly lower for cooler regions (A and B) than for warmer regions (C, D, and E). When comparing case 5 (ASHP + AE) to case 4 (ASHP) for cool regions, a TCO decrease of up to 32% is reported for region A because the AE is expected to be used significantly throughout the year; therefore, reducing the LEC and LOM costs considerably. On the other hand, the TCO in warm regions is higher for case 5 than for case 4 because of the additional CAP and LOM costs of purchasing, installing, and operating the AE.

Nationwide summary results of the TCO, CAP and LOM costs, LEC, LCO_2e emissions, and lifetime average COP are provided in Figure 4.29. ASHP + AE applications in cool regions are attractive options for cooling cellular tower shelters because of lower TCO and LOM costs; however, warm regions incur higher costs and do not benefit from use of AEs. In this study, the AE setpoint temperature of 10 °C is too low for application in regions with warm climates. Several AE setpoint temperatures are explored for case 5 in section 4.4, and the TEEP sensitivity is analyzed and compared nationwide.

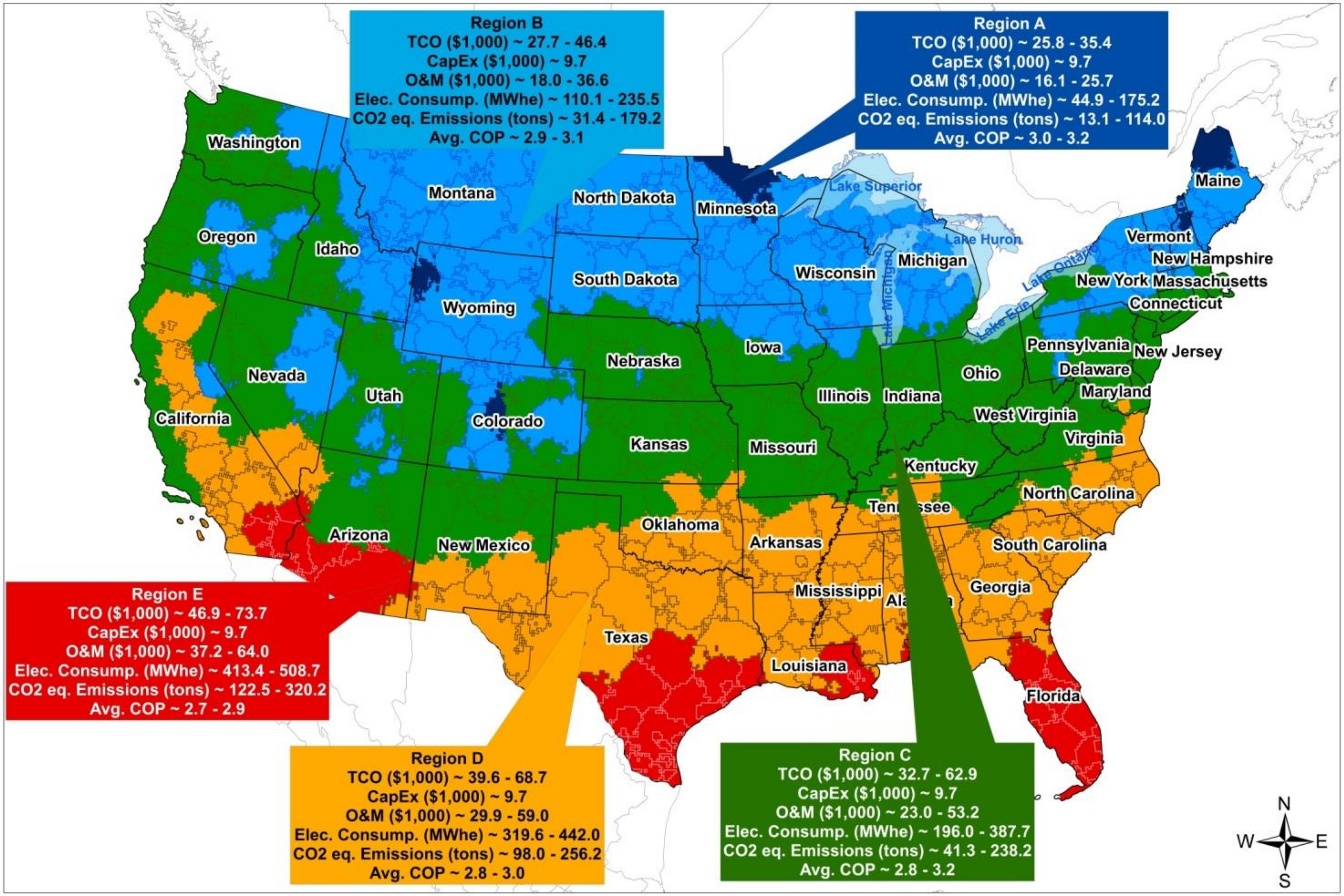

Figure 4.29 - Summary of the technical, economic, and environmental performance (TEEP) of all 545 TMY3 weather boundaries for case 5: ASHP + AE.

4.3.6: Summary and Major Findings

To compare the TEEP of the five cooling configurations, major findings for six geographic locations in the U.S. representative of various climatic regions are summarized in Table 4.14 and figures 4.30 – 4.32. The illustrated results incorporate the base case parameters provided in Table 4.8 (Section 4.3) and the case studies simulated in sections 4.3.1 – 4.3.5.

Table 4.14 – Total cost of ownership (TCO, $), lifetime electricity consumption (LEC, MWhe), and lifetime CO_2e emissions (LCO_2e, tons) by cooling configuration for six geographic locations nationwide in different climatic regions.

			Cooling Configuration				
Climatic Region	**City, State**	**Metric**	**Case 1: GHP-only**	**Case 2: GHP + AE**	**Case 3: GHP + DC**	**Case 4: ASHP-only (BAU)**	**Case 5: ASHP + AE**
Experimental Site	Varna, NY (Experimental site)	TCO ($)	61,300	45,800	58,500	54,700	41,200
		LEC (MWhe)	348	157	366	403	214
		LCO_2e (tons)	65	29	68	75	40
A	Caribou, ME	TCO ($)	56,100	38,500	57,100	51,300	35,400
		LEC (MWhe)	354	127	385	379	157
		LCO_2e (tons)	103	37	112	110	46
B	Minneapolis, MN	TCO ($)	48,100	39,300	49,200	47,100	37,200
		LEC (MWhe)	282	131	344	400	213
		LCO_2e (tons)	183	85	224	260	139
C	Denver, CO	TCO ($)	52,300	43,600	49,400	47,600	39,000
		LEC (MWhe)	296	160	326	416	243
		LCO_2e (tons)	246	133	271	346	202
D	Sacramento, CA	TCO ($)	69,400	62,400	65,300	64,600	58,500
		LEC (MWhe)	322	232	325	441	347
		LCO_2e (tons)	95	69	96	131	103
E	Miami, FL	TCO ($)	96,900	100,700	78,500	53,700	57,500
		LEC (MWhe)	362	359	469	501	499
		LCO_2e (tons)	185	184	241	257	256

In Figure 4.30, the TCO for all configurations is the lowest for states located in cool climatic regions (e.g., Maine, Minnesota, Colorado). In states with cool climates, the LEC is significantly lower than states with warm climates, and less total BHE length is required for the GHP configurations (under 270 m for some regions). For example, Caribou, ME has the lowest TCO for case 2 (GHP + AE) because its cold climate allows for frequent use of AE during the year. The use of AE reduces CAP and LOM costs due to lower total BHE length of the GHP system and lower LEC, respectively.

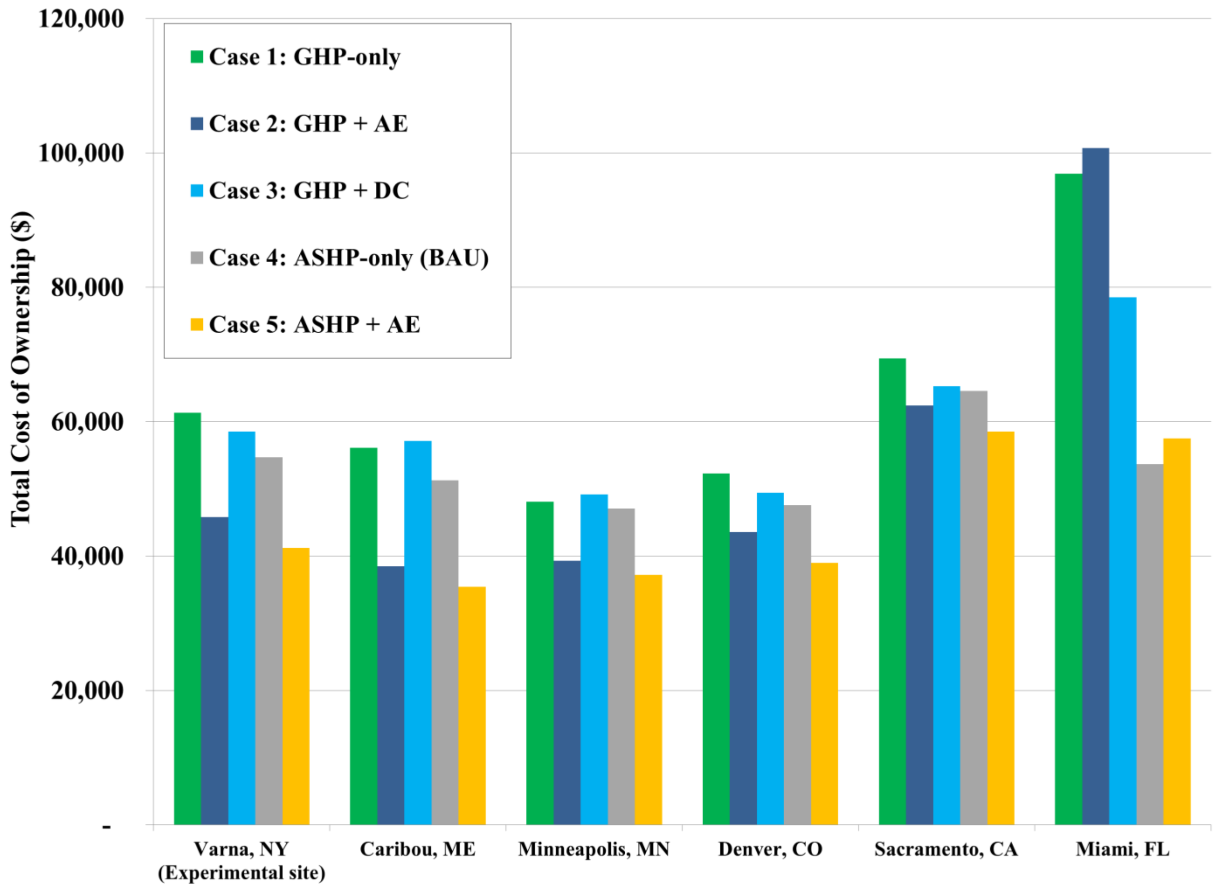

Figure 4.30 – Total cost of ownership (TCO, $) for five cooling configurations by geographic locations nationwide in different climatic regions.

The TCO for all cooling configurations in Figure 4.30 are the highest for states located in warm climatic regions (e.g., California, Florida). To provide continuous cooling in warm regions, more electricity is consumed over the lifetime of the systems, and larger total BHE lengths are required for GHP configurations (up to 1,080 m for some regions). In regions requiring significant total BHE lengths, the CAP costs of installing GHPs can be as high as eight times the cost of ASHPs.

With the exception of Miami, FL, the configuration with the lowest overall TCO is case 5 (ASHP + AE) followed by case 2 (GHP + AE). The configuration with the highest overall TCO is case 1 (GHP-only) followed closely by case 3 (GHP + DC) and case 4 (ASHP-only). In warm climatic states (e.g., Florida), installing AEs is not recommended because the small fraction of the year when the AE is used does not justify the added costs of installation, operation, and maintenance.

In Figure 4.31, the configuration with the lowest LEC is case 2 followed by case 5. The configuration with the highest overall LEC is case 4 followed by case 3 and case 1. Similarly, the LCO_2e emissions are the lowest for case 2, and the highest for case 4. In Figure 4.32, the LCO_2e emissions in Colorado for case 4 are almost a factor of three greater than case 2. Colorado has high LCO_2e emissions because its electricity generation resource mix is primarily coal (~70%) (see Table 4.7 in Section 4.2.6).

Even though all five cooling configurations in Florida consume the highest amount of electricity among the geographic locations considered, their environmental impacts are lower than those of states that consume less electricity because Florida's electricity generation mix is primarily natural gas (~68%). As expected, upstate New York results in the lowest lifetime CO_2e emissions for all configurations and geographic locations because its electricity generation resource mix is based on low CO_2 emitting energy sources.

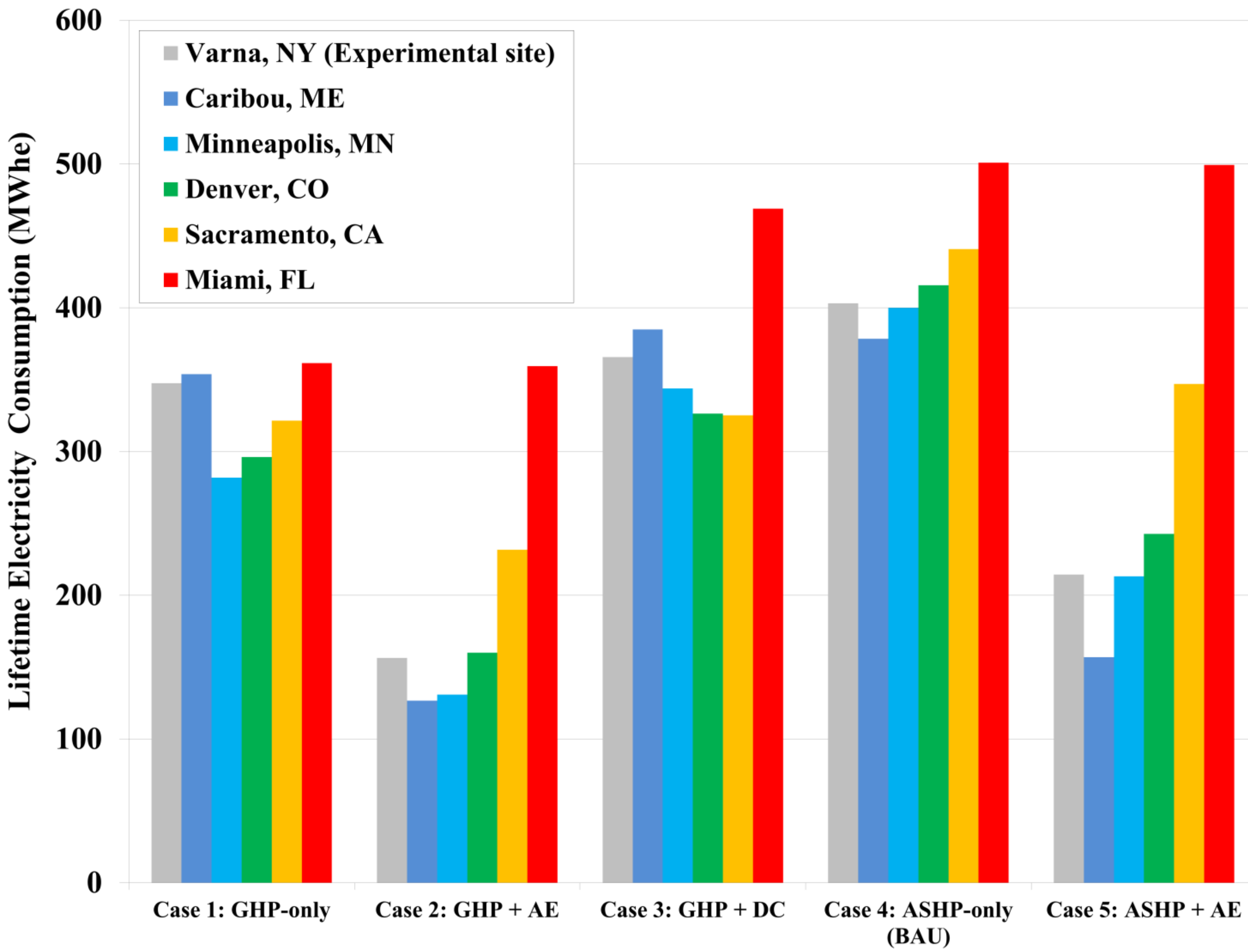

Figure 4.31 – Lifetime Electricity Consumption (LEC, MWhe) for six geographic locations nationwide in different climatic regions by cooling configuration.

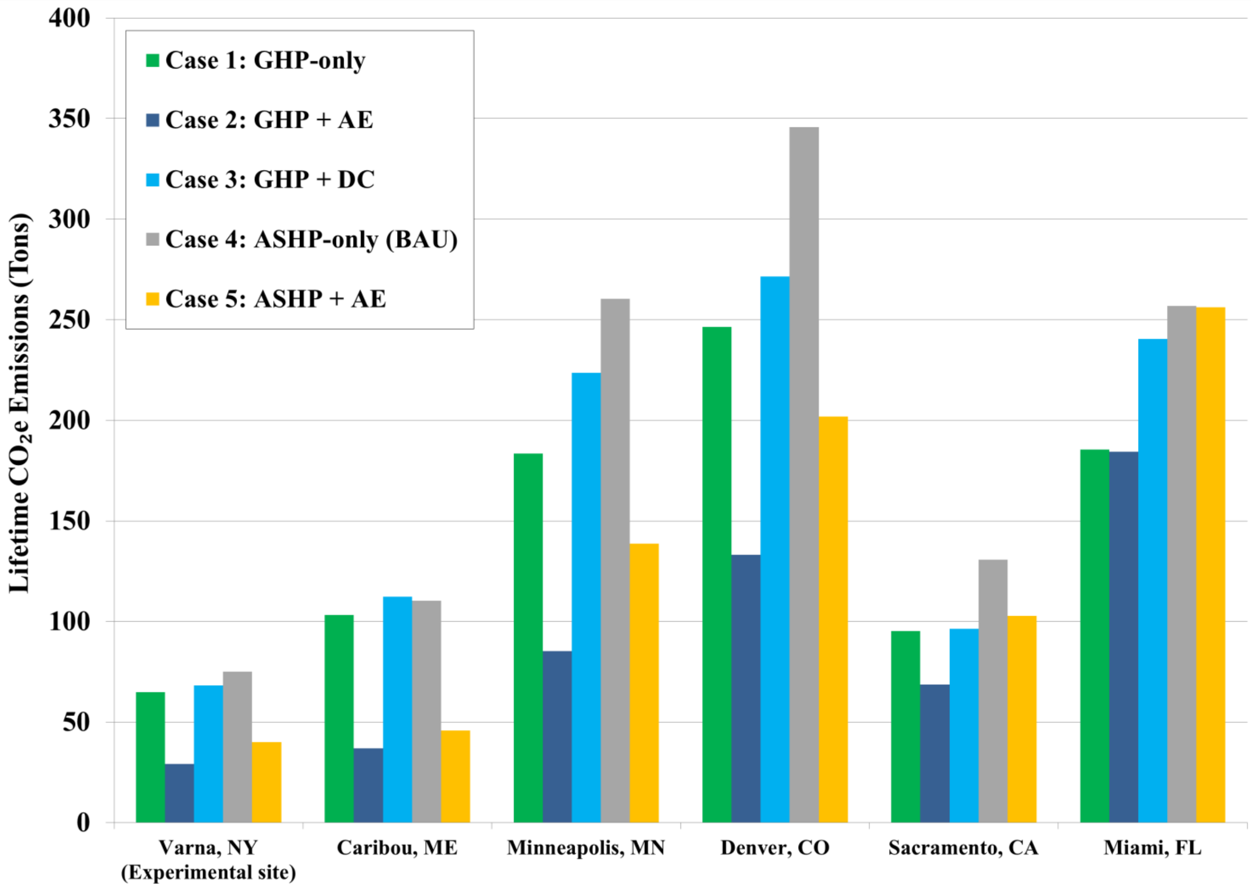

Figure 4.32 – Lifetime CO_2e Emissions (LCO_2e, Tons) for five cooling configurations by geographic locations nationwide in different climatic regions.

Electricity consumption of GHP systems vary depending on the coefficient of performance (COP). In this study, a representative total borehole length was chosen for each climatic region to provide a COP of at least 3.5. Typical GHP COP's can range from 3 to 6, which means that for one unit of electricity input, the GHP provides 3 to 6 units of cooling capacity (Glassley, 2010; Beckers, 2016). Lower LEC and LCO_2e emissions for GHP systems can be achieved by increasing the total BHE length, which improves the COP of the system (Beckers, 2016).

In this section, the base case results for five cooling configurations nationwide represent an approximation of the expected system performance based on available data in Section 4.2 and the modeling efforts in sections 4.3.1 – 4.3.5. To improve the accuracy and increase the spatial resolution at any particular location, it is necessary to perform detailed hydrogeological and climatic analyses, as well as establish economic and environmental metrics that are representative of that exact geographic location. To assess the impacts of parameter variations on the TEEP of the five cooling configurations, a sensitivity analysis of the parameters discussed in Table 4.8 is provided in Section 4.4 across various geographic regions.

4.4: Sensitivity Analysis of the Technical, Economic, and Environmental Performance (TEEP) of Five Cooling Configurations

In this section, a sensitivity analysis of the TEEP for cases 1 – 5 across six geographic locations in the U.S. is presented. The objectives are to assess the TEEP impacts of technical and financial parameter variations, and to provide recommendations for future research of hybrid GHP systems for cooling-dominated applications. The work presented in this section incorporates analyses and results discussed in sections 4.2 and 4.3.

Sensitivity analysis allows for the identification of parameters that exert the most influence on the performance of a model. Through a sensitivity analysis, parameters that are more influential may be further studied and refined, and those that are less influential may be disregarded from the model. Various methods exist to assess the sensitivity analysis of model parameters, including varying parameter values one-at-a-time by a fixed amount (Hamby, 1994).

To assess the sensitivity of GHP and ASHP model parameters on the life cycle cost (LCC) of the systems, Mun et al. (2012) performed a one-at-a-time sensitivity analysis on the

CAP and LOM costs. For GHP systems, electricity costs exerted the most influence on the LCC, followed by CAP costs. For ASHP systems, maintenance costs had the most influence on the LCC, followed by electricity costs.

At the Varna site, Beckers (2016) assessed the sensitivity in the TCO of hybrid GHP and ASHP systems from variations in the cellular tower shelter heat generation, reservoir thermal conductivity, and costs. For both the hybrid GHP and ASHP systems, the TCO is low under scenarios with low shelter heat generation and electricity rates. For all GHP systems, the TCO is low under scenarios with high reservoir thermal conductivity and low capital expenditure costs from drilling of the BHE field (Beckers, 2016).

To assess the TEEP sensitivity from technical and financial parameter variations of hybrid GHP and ASHP systems, a one-at-a-time sensitivity analysis was conducted on the parameters listed in tables 4.15 and 4.16. From Table 4.15, increases in the total BHE length and variations on the estimated formation thermal conductivity ($K_{f,s}$) of GHP systems (cases 1 – 3) are considered to assess the performance of technical (COP, LEC, LCO_2e) and economic (TCO) variables. It is expected that increases in the total BHE length and $K_{f,s}$ from base case scenario will improve the performance (COP) of the GHP systems and decrease the TCO. Furthermore, different AE temperature setpoints are explored in the hybrid GHP and ASHP configurations to assess the TEEP performance of weather boundaries located in various climatic regions.

Table 4.15 – Technical parameters for the one-at-a-time sensitivity analysis of hybrid GHP and ASHP configurations.

Cooling Configuration	**Technical Parameter**	**Simulation Change**	**Effect on**			
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC	Total Borehole (BHE) Length	Increases in the total BHE length from base case	Average Lifetime COP	TCO	LEC	LCO_2e emissions
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC	Formation Thermal Conductivity ($K_{f,s}$)	Low $K_{f,s}$ of 1.2 W/m·K and $K_{f,s}$ under groundwater advection	Average Lifetime COP	TCO	LEC	LCO_2e emissions
Case 2: GHP+AE Case 5: ASHP+AE	AE Setpoint Temperature	± 5°C from base case of 10°C *(5°C, 15°C)*	Average Lifetime COP	TCO	LEC	LCO_2e emissions

From Table 4.16, the financial parameters sensitivity analysis considers the effect in the TCO from variations in the CAP and O&M costs, and consideration of incentives for energy-efficient technology. In order to assess the local linearity in the output of the model (TCO), the sensitivity analysis considers small and large perturbations in the financial input parameters from base case scenario. Specifically, the effect in the TCO from a ± 10% and ± 50% change in the unit capital expenditure, drilling costs, operating costs (electricity rates), maintenance costs, and installation costs from base case scenario are considered.

The availability of incentives for energy-efficient technology, including GHP systems, is considered in the TCO effect of cases 1 – 3. Currently, a 10% federal tax credit is available for energy-efficient property in commercial installations. However, more aggressive incentives in the future may remove some of the barriers to larger deployment of GHP systems.

Table 4.16 – Financial parameters for the one-at-a-time sensitivity analysis of hybrid GHP and ASHP configurations.

Cooling Configuration	Financial Parameter	Simulation Change	Effect on
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC Case 4: ASHP Case 5: ASHP+AE	Unit Capital Expenditure (GHP, AE, DC, ASHP)	± 10%, 50% from base case	TCO
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC	Drilling Costs	± 10%, 50% from base case	TCO
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC Case 4: ASHP Case 5: ASHP+AE	Electricity Rates	± 10%, 50% from base case	TCO
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC	Installation Costs (pumps, piping & installation)	± 10%, 50% from base case	TCO
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC Case 4: ASHP Case 5: ASHP+AE	Maintenance Costs	± 10%, 50% from base case	TCO
Case 1: GHP Case 2: GHP+AE Case 3: GHP+DC	Incentives	- 10%, - 50% from base case	TCO

For cases 1 – 5, sections 4.4.1 and 4.4.2 provide the TEEP sensitivity analysis for one-at-a-time variations of technical and financial parameters, respectively, across various geographic locations in the U.S. In Section 4.4.3, a summary of major findings and recommendations on the TEEP sensitivity of five cooling configurations nationwide is provided.

4.4.1: TEEP Sensitivity Analysis of Hybrid GHP and ASHP Systems from Variations in Technical Parameters

In this section, the sensitivity analysis of hybrid GHP and ASHP systems consider the TEEP impacts of variations in technical parameters that include total BHE length, $K_{f,s}$, and AE setpoint temperature (see Table 4.15 in Section 4.4). The TEEP impacts are discussed for six geographic locations nationwide (see Section 4.3). For cases 1 – 3, the six geographic locations include: Varna, NY (experimental site) and Denver, CO for case 1 (GHP-only); Caribou, ME and Miami, FL for case 2 (GHP + AE); and Minneapolis, MN and Sacramento, CA for case 3 (GHP + DC). For each case study, summary results for all geographic locations are provided in tables A.1 – A.18 of Appendix A.

Total Borehole (BHE) Length Variability

For GHP systems (cases 1 – 3), the sensitivity analysis evaluates the TEEP impacts from increases in the total BHE length from base case scenario. The TEEP impacts from a decrease of the total BHE length were not considered in this study because of interests to ensure a COP in the GHP system of at least 3.5 (see Section 3.3).

Case 1: TEEP Sensitivity Analysis for Varna, NY and Denver, CO

For case 1, the TEEP impacts of increasing the total BHE length from base case scenario in Varna and Denver are provided in Figure 4.33. In Varna, the base case total BHE length is 220 m. The total BHE length in Varna is increased to 250 m and 330 m representing a 14% and 50% increase from base case, respectively. From Figure 4.33, increasing the total BHE length in Varna results in improved lifetime average COP, lower LEC and LCO_2e emissions, and lower TCO.

Specifically, increasing the total BHE length to 250 m increases the COP by almost 13%, and reduces the LEC/LCO$_2$e emissions and TCO by around 11% and 3% from base case, respectively. Increasing the total BHE length to 330 m increases the COP by over 30%, and reduces the LEC/LCO$_2$e emissions and TCO by over 23% and 2% from base case, respectively.

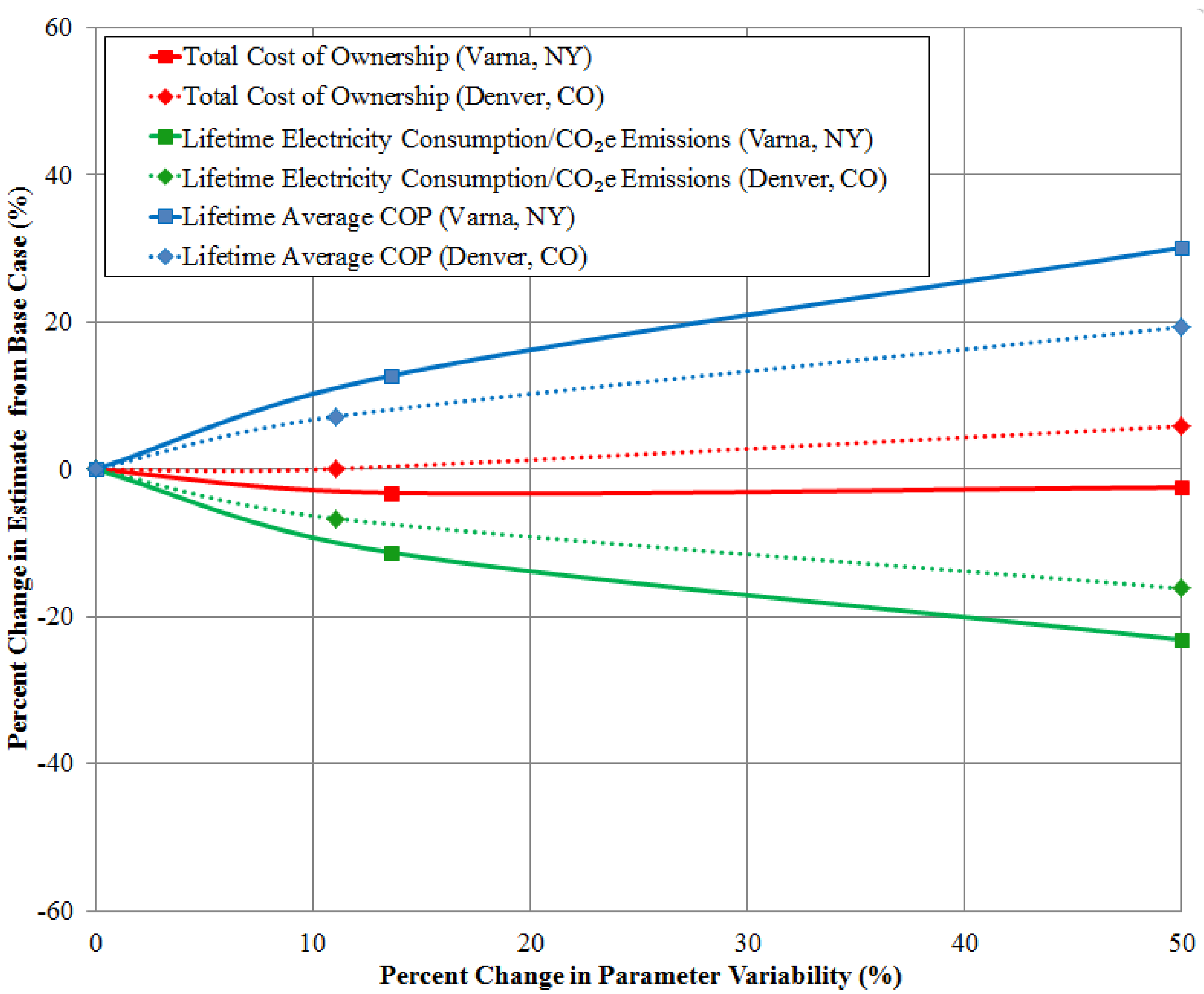

Figure 4.33 – Total BHE length sensitivity analysis for case 1 (GHP – only) in Varna, NY and Denver, CO.

In Denver, the base case total BHE length is 270 m. The total BHE length is increased to 300 m and 405 m representing an increase of 11% and 50% from base case, respectively. From Figure 4.33, increasing the total BHE length to 300 m and 405 m increases the COP by over 7%

and 19% from base case, respectively. An increase in the total BHE length in Denver results in a decrease in the LEC/LCO$_2$e emissions, but an increase in the TCO. For instance, increasing the total BHE length to 405 m decreases the LEC/LCO$_2$e emissions by over 16% from base case, but increases the TCO by over 5%. Unlike the Varna site, the TCO in Denver does not decrease with increasing length because Denver requires longer BHE lengths, which increases CAP costs. Denver is located in a warmer climatic region than Varna; therefore, the cooling load is higher requiring a larger geothermal BHE field.

Case 2: TEEP Sensitivity Analysis for Caribou, ME and Miami, FL

In Figure 4.34, the TEEP impacts of increasing the total BHE length for case 2 (GHP + AE) in Caribou and Miami are provided. In Caribou, the base case total BHE length is 100 m. Increasing the total BHE length to 110 m and 150 m represents an increase of 10% and 50% from base case, respectively. An increase of the total BHE length by 10% and 50% increases the COP by over 11% and 49% from base case, respectively. As a result of the improved GHP + AE performance, the LEC/LCO$_2$e emissions decrease by over 10% and 32% from base case when the total BHE length is increased by 10% and 50%, respectively. Furthermore, a decrease of around 2% in the TCO is observed for the Caribou, ME weather boundary when the total BHE length increases to 110 m and 150 m.

In Miami, the base case total BHE length is over 1,000 m. The total BHE length is increased to 1,200 m and 1,500 m representing an 11% and 39% increase from base case, respectively. From Figure 4.34, an increase in the total BHE length to 1,200 m results in an increase of over 2% in the COP of the system and a decrease of over 2% in the LEC/LCO$_2$e emissions from base case.

If the total BHE length in Miami is increased to 1,500 m, the COP increases to over 6% and the LEC/LCO_2e emissions decrease by over 5% from base case. However, any increases in the total BHE length of the geothermal field in Miami results in higher CAP costs because of the high cooling load of the area. If the total BHE length is increased to 1,200 m and 1,500 m, the TCO increases by around 5% and 19% from base case, respectively. The largest increase in the total BHE length in Miami was 1,500 m because the TRNSYS-MATLAB simulations for such a large BHE field resulted in longer than expected simulation times.

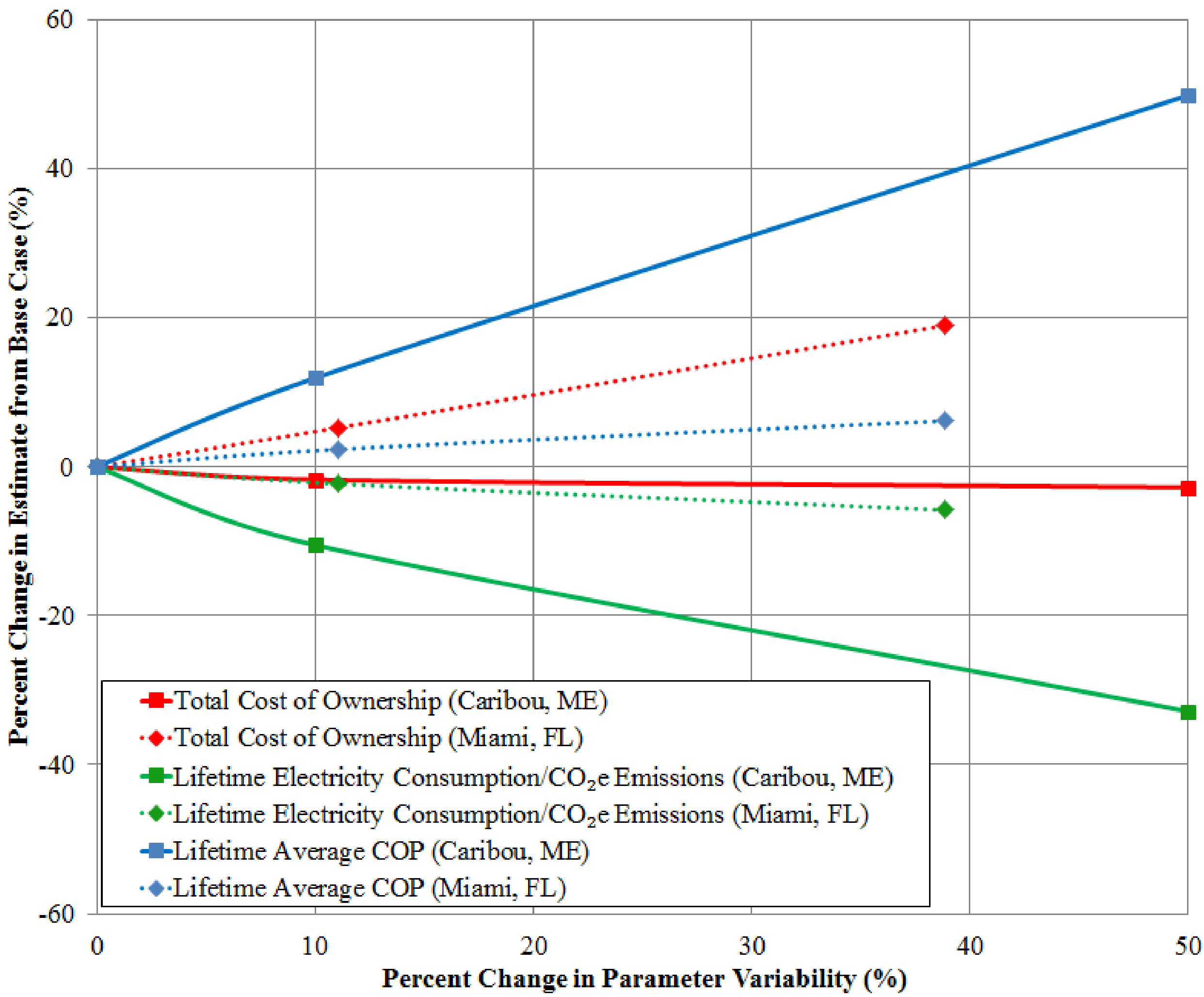

Figure 4.34 – Total BHE length sensitivity analysis for case 2 (GHP + AE) in Caribou, ME and Miami, FL.

Case 3: TEEP Sensitivity Analysis for Minneapolis, MN and Sacramento, CA

In Figure 4.35, the TEEP impacts of increasing the total BHE length for case 3 (GHP + DC) in Minneapolis and Sacramento are provided. In Minneapolis, the base case total BHE length is 110 m. The total BHE length is increased to 130 m and 170 m representing an 18% and 55% increase from base case, respectively. Similar to the previous cases considering weather boundaries in cool climatic regions, an increase in the total BHE length in Minneapolis from base case improves the COP of the system, and decreases the LEC/LCO$_2$e emissions and TCO.

Specifically, an increase in the total BHE length to 130 m and 170 m in Minneapolis results in a COP increase of over 14% and 33% from base case, respectively. The LEC/LCO$_2$e emissions decrease by over 20% from base case when the total BHE length is increased to 170 m. A small decrease of over 3% and 5% is observed in the TCO from base case when the total BHE length is increased to 130 m and 170 m, respectively. For weather boundaries located in cool climates (regions A and B in Figure 4.3), increases in the COP significantly reduces the LEC/LCO$_2$e emissions and LOM costs resulting in reductions in the TCO, even when CAP costs from drilling operations increase.

As expected in areas with warm climates (regions D and E), increases in the total BHE length from base case results in a marginal increase in the COP and decrease in the LEC/LCO$_2$e emissions, and an increase in the TCO. From Figure 4.35, the base case total BHE length in Sacramento is 240 m, and the length is increased to 270 m and 360 m, representing a 12% and 50% increase from base case, respectively. When the total BHE length is increased to 270 m, the COP increases by over 1%, LEC/LCO$_2$e emissions decrease by around 1%, and TCO increases by roughly 2% from base case. An increase in the total BHE length to 360 m, increases the COP and TCO by over 3% and 7% from base case, respectively.

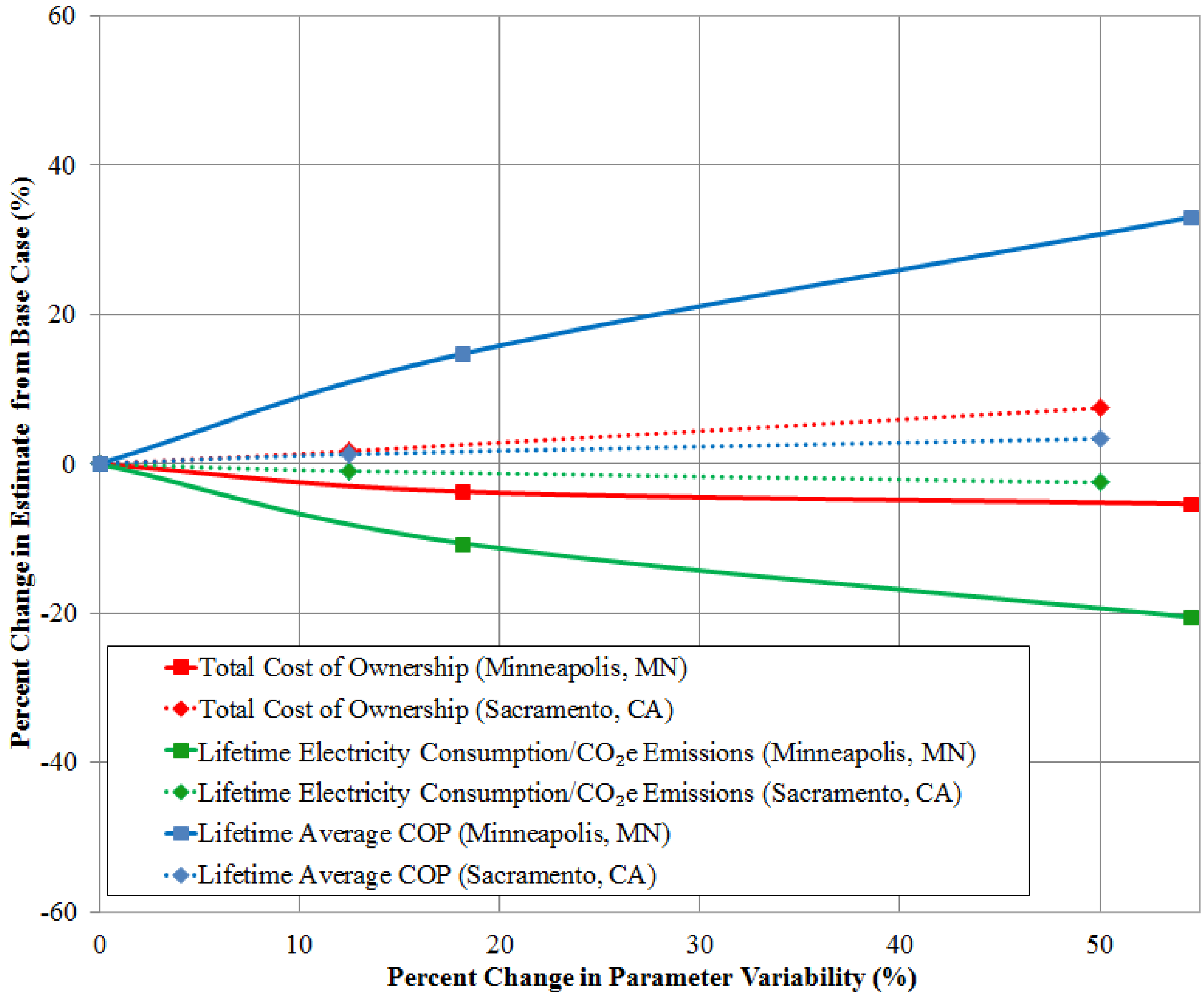

Figure 4.35 – Total BHE length sensitivity analysis for case 3 (GHP + DC) in Minneapolis, MN and Sacramento, CA.

Formation Thermal Conductivity ($K_{f,s}$) Variability

The sensitivity analysis considering variations in the formation thermal conductivity ($K_{f,s}$) for GHP systems (cases 1 – 3) evaluates the TEEP impacts from a decrease and increase in the base case $K_{f,s}$ estimates. From Table 4.8 in Section 4.3, the base case scenario for the GHP systems considers mean conduction-only $K_{f,s}$ estimates based on indirect methods to assess the ground thermal properties at each site (see Section 4.2.4). In this study, variations in the $K_{f,s}$ for each geographic location is assessed based on the $K_{f,s}$ case studies by groundwater region and rock classifications presented in Table 4.5 of Section 4.2.4.

Case 1: TEEP Sensitivity Analysis for Varna, NY and Denver, CO

In Varna, a representative base case mean conduction-only $K_{f,s}$ was estimated to be 2.2 W/m·K. To assess the TEEP impacts from site variations in the $K_{f,s}$, a range of estimated values were considered: 1.2 W/m·K, 3.7 W/m·K, and 6.2 W/m·K. The $K_{f,s}$ value of 1.2 W/m·K represents a lower bound, while the values of 3.7 W/m·K and 6.2 W/m·K correspond to cases D and F, respectively, from Table 4.5 of Section 4.2.4. Cases D and F are indicative of groundwater flow presence at the site. The Varna weather boundary is located in the Glaciated Central Region of the groundwater regions classification by Thomas (1952) and Heath (1984). The Glaciated Central Region is characterized by glacial deposits underlain by fractured sedimentary rocks that may include sandstone, shale, limestone, and dolomite, among other rocks (Thomas, 1952; Heath, 1984).

In Denver, a representative base case mean conduction-only $K_{f,s}$ was estimated at 2.4 W/m·K and variations in the $K_{f,s}$ ranged from 1.2 W/m·K, 3.7 W/m·K, and 6.6 W/m·K. Similarly, a $K_{f,s}$ value of 1.2 W/m·K represents a lower bound, and values of 3.7 W/m·K and 6.6 W/m·K correspond to cases D and F (see Table 4.5 of Section 4.2.4). The Denver weather boundary intersects several groundwater regions, including the Western Mountain Ranges, High Plains, and Nonglaciated Central Region. The Western Mountain Ranges are characterized by thin soils overlying fractured rocks of granitic and metamorphic composition. The High Plains and Nonglaciated Central Region are characterized by thick alluvial deposits and thin regolith, respectively, overlying fractured sedimentary rocks (Thomas, 1952; Heath, 1984).

For case 1, the TEEP impacts of variations in the $K_{f,s}$ in Varna and Denver are provided in Figure 4.36. From Figure 4.36, a decrease of the estimated $K_{f,s}$ (1.2 W/m·K) in both Varna and Denver result in a significant decrease of the GHP performance (COP), and increase in the LEC/LCO$_2$e emissions and TCO from base case. If the $K_{f,s}$ of the site results in lower than the estimated base case scenario, the COP at both sites decreases by over 40% and the LEC/LCO$_2$e emissions increase by over 80% from base case. On the other hand, any increase on the $K_{f,s}$ from the base case scenario results in improved COP, and lower LEC/LCO$_2$e emissions and TCO.

In Varna, an increase of the $K_{f,s}$ to 3.7 W/m·K from base case (2.2 W/m·K) results in a COP increase of around 40%, LEC/LCO$_2$e emissions reductions by over 28%, and TCO reductions by over 14%. The TCO reductions are a result of a decrease in the operating costs of the GHP system from lower LEC. In Denver, a similar $K_{f,s}$ increase results in a COP improvement of over 20%, LEC/LCO$_2$e emissions reductions of over 17%, and TCO reduction of 7% from base case.

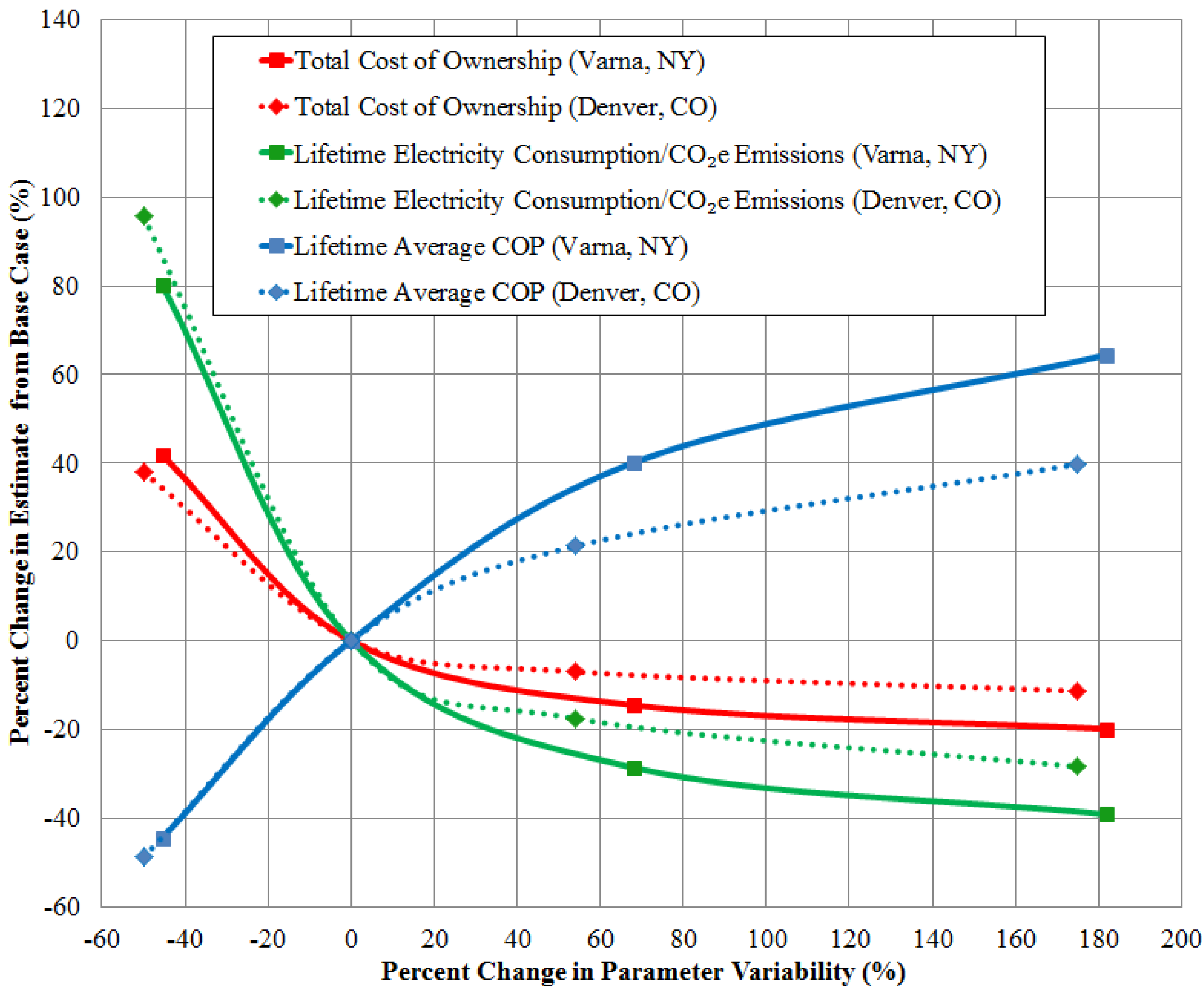

Figure 4.36 – Formation thermal conductivity ($K_{f,s}$) sensitivity analysis for case 1 (GHP -only) in Varna, NY and Denver, CO.

Case 2: TEEP Sensitivity Analysis for Caribou, ME and Miami, FL

In Caribou, a base case mean conduction-only $K_{f,s}$ was estimated at 3.0 W/m·K and variations in the $K_{f,s}$ ranged from 1.2 W/m·K, 4.6 W/m·K, and 6.6 W/m·K. The Caribou weather boundary is characterized by the Northeast and Superior Uplands groundwater region. The Northeast and Superior Uplands region is distinguished by glacial deposits underlain by fractured crystalline rocks that may include granite, anorthosite, and quartzite, among other rocks (Thomas, 1952; Heath, 1984).

The Miami weather boundary encompasses the Southeast Coastal Plain groundwater region, which is distinguished by thick layers of unconsolidated deposits including sand, gravel, and clay underlain by limestone and dolomite rocks (Thomas, 1952; Heath, 1984). For this study, a base case mean conduction-only $K_{f,s}$ for Miami was estimated at 2.1 W/m·K, and variations in the $K_{f,s}$ ranged from 1.2 W/m·K, 4.1 W/m·K, and 6.2 W/m·K.

For case 2, the TEEP impacts of variations in the $K_{f,s}$ in Caribou and Miami are provided in Figure 4.37. In Caribou, a decrease of the $K_{f,s}$ (1.2 W/m·K) from base case (3.0 W/m·K) results in a significant decrease of the GHP + AE performance (COP), and increase in the LEC/LCO_2e emissions and TCO. Specifically, the COP of the GHP system in Caribou decreases by over 40%, and the LEC/LCO_2e emissions and TCO increases by over 70% and 23% from base case, respectively. In Miami, a decrease of the $K_{f,s}$ (1.2 W/m·K) from base case (2.1 W/m·K) results in a COP decrease of over 17%, and an increase in the LEC/LCO_2e emissions and TCO of over 20% and 5%, respectively.

On the other hand, increases on the $K_{f,s}$ from base case scenario in Caribou results in a significant improvement on the performance and costs of the system. For instance, a $K_{f,s}$ of 4.6 W/m·K increases the COP by over 33%, and reduces the LEC/LCO_2e emissions and TCO by over 24% and 7% from base case, respectively. In Miami, a $K_{f,s}$ increase of 4.1 W/m·K increases the COP by over 12%, and reduces the LEC/LCO_2e emissions and TCO by over 10% and 2% from base case, respectively.

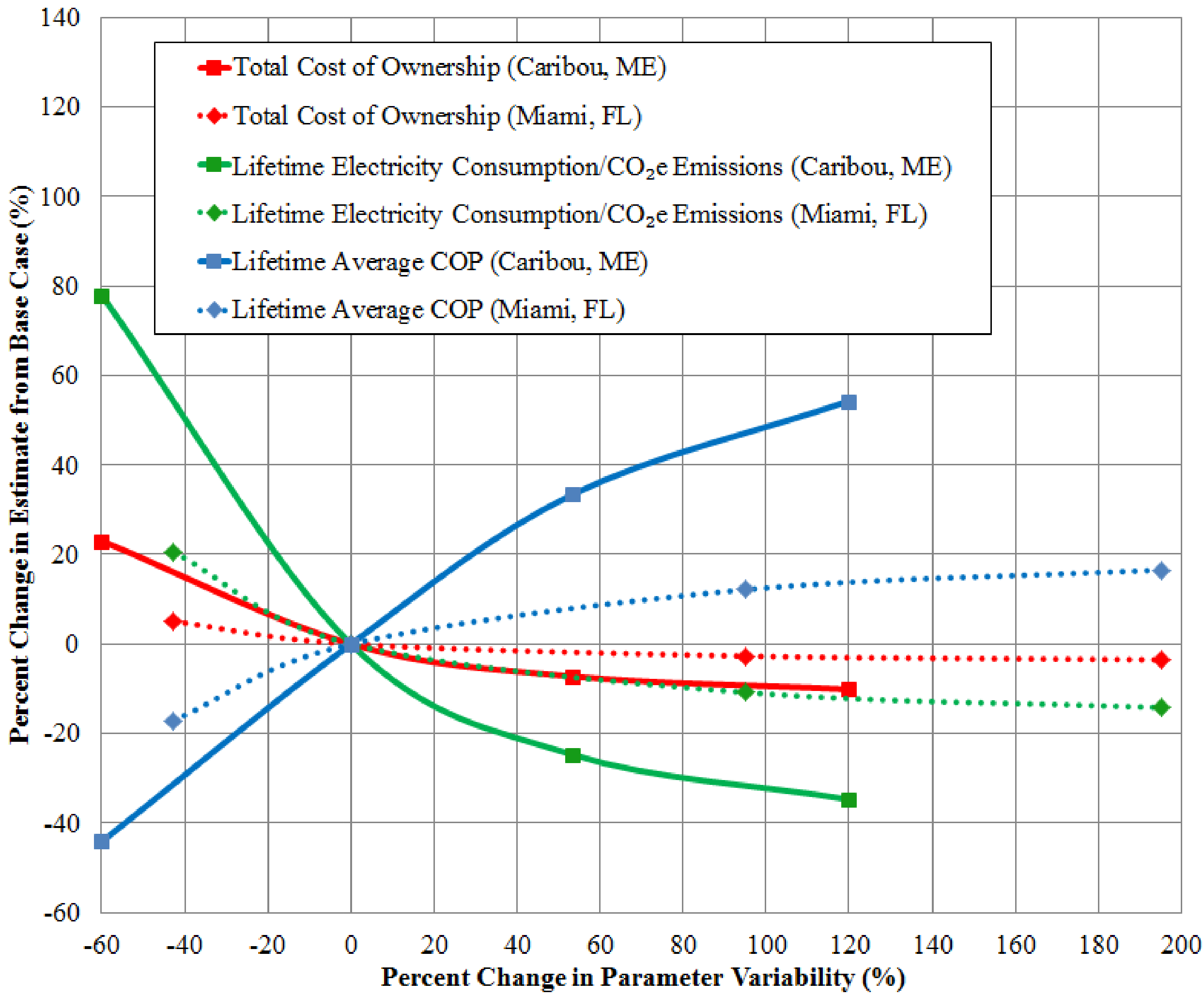

Figure 4.37 – Formation thermal conductivity ($K_{f,s}$) sensitivity analysis for case 2 (GHP + AE) in Caribou, ME and Miami, FL.

For cooling-dominated applications, GHP + AE systems in cool climatic regions benefit from small geothermal BHE fields and improved system performance. Therefore, any significant changes in the BHE thermal field properties in cool climatic regions is likely to significantly affect the performance and costs of the hybrid system. On the other hand, warm climatic regions do not benefit as much from hybrid GHP applications, and require large BHE fields. Significant changes in the BHE thermal field properties in warm climatic regions have less of an effect on the performance and costs of the hybrid system.

Case 3: TEEP Sensitivity Analysis for Minneapolis, MN and Sacramento, CA

In Minneapolis, a base case mean conduction-only $K_{f,s}$ was estimated at 2.6 W/m·K and variations in the $K_{f,s}$ ranged from 1.2 W/m·K, 4.5 W/m·K, and 6.2 W/m·K. Similar to the Varna weather boundary, Minneapolis is part of the Glaciated Central Region and is characterized by glacial deposits underlain by fractured sedimentary rocks (Thomas, 1952; Heath, 1984). On the other hand, the Sacramento weather boundary intersects several groundwater regions, including the Western Mountain Ranges and Alluvial Basins. The Alluvial Basins are characterized by thick alluvial deposits bordered by mountains (Thomas, 1952; Heath, 1984). In Sacramento, a base case mean conduction-only $K_{f,s}$ was estimated at 2.5 W/m·K and variations in the $K_{f,s}$ ranged from 1.2 W/m·K, 4.0 W/m·K, and 6.2 W/m·K.

For case 3, the TEEP impacts of variations in the $K_{f,s}$ in Minneapolis and Sacramento is provided in Figure 4.38. A decrease of the Minneapolis regional $K_{f,s}$ (1.2 W/m·K) from base case (2.5 W/m·K) results in a significant decrease of the GHP + DC performance (COP), and increase in the LEC/LCO_2e emissions and TCO. Specifically, the COP of the GHP system in Minneapolis decreases by over 20%, and the LEC/LCO_2e emissions and TCO increases by over 22% and over 11% from base case, respectively. In Sacramento, a decrease of the $K_{f,s}$ (1.2 W/m·K) from base case (2.5 W/m·K) also results in a decrease of the COP and increase in costs. Specifically, a COP decrease of over 9%, and an increase in the LEC/LCO_2e emissions and TCO of over 7% and 4% from base case, respectively, is observed

As expected, increases on the $K_{f,s}$ from base case scenario in both Minneapolis and Sacramento result in improved TEEP of the GHP + DC system. Similar to cases 1 and 2, the magnitude of the increase in performance and decrease of costs from higher $K_{f,s}$ is larger in regions with cooler climates and smaller in regions with warmer climates. From Figure 4.8, a

$K_{f,s}$ of 4.5 W/m·K in Minneapolis increases the COP by roughly 28%, and reduces the LEC/LCO$_2$e emissions and TCO by over 18% and 9% from base case, respectively. The improvement in performance and costs in Minneapolis is significantly larger with $K_{f,s}$ over 6 W/m·K. In Sacramento, a $K_{f,s}$ increase of 4.0 W/m·K increases the COP by almost 3%, and reduces the LEC/LCO$_2$e emissions and TCO by over 2% and 1% from base case, respectively. The improvement in the system performance and costs in Sacramento is marginal even with a $K_{f,s}$ increase by over 6.0 W/m·K.

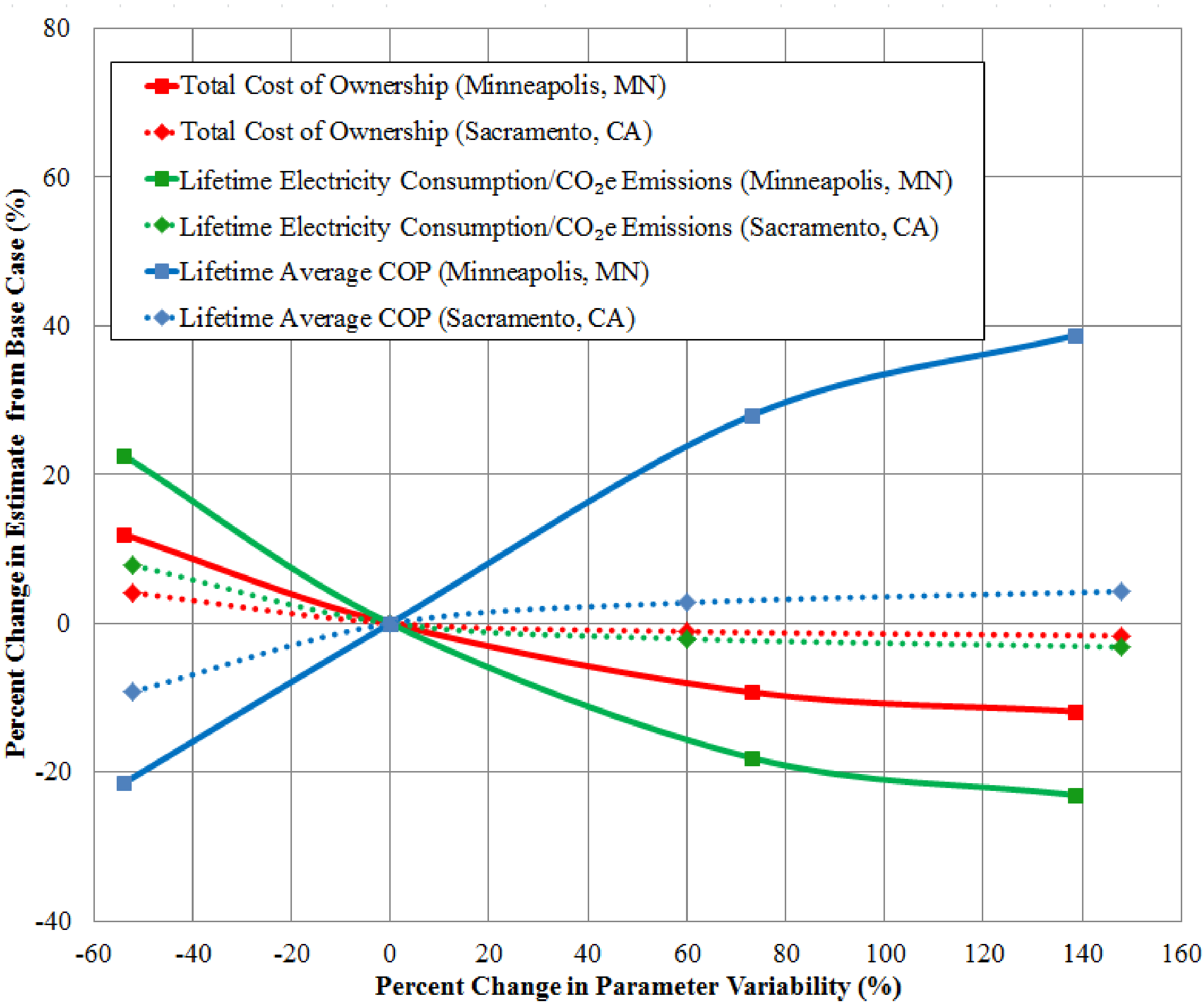

Figure 4.38 – Formation thermal conductivity ($K_{f,s}$) sensitivity analysis for case 3 (GHP + DC) in Minneapolis, MN and Sacramento, CA.

Air Economizer (AE) Temperature Setpoint Variability

The TEEP impacts for case 2 (GHP + AE) and case 5 (ASHP + AE) consider variations in the AE temperature setpoint for two geographic locations in distinct climatic regions. The geographic locations include Caribou, ME in climatic region A and Miami, FL in climatic region E (see Figure 4.3 in Section 4.2). For all geographic locations considered in sections 4.2 and 4.3, the base case AE temperature setpoint for cases 2 and 5 is 10 °C. The base case AE temperature setpoint was originally investigated at the experimental site in Varna, and defined as a base case scenario nationwide (see Table 4.8 in Section 4.3). From Section 4.3.2, the base case AE temperature setpoint primarily benefits weather boundaries located in cool climatic regions. Therefore, the sensitivity analysis for AE units includes variations of ± 50% in the temperature setpoint.

Case 2: TEEP Sensitivity Analysis for Caribou, ME and Miami, FL

For case 2, the TEEP impacts of variations in the AE temperature setpoint in Caribou and Miami is provided in Figure 4.39. In Caribou, when the AE temperature setpoint decreases to 5 °C the COP of the GHP + AE system decreases by over 9%, and the LEC/LCO_2e emissions and TCO increase by over 55% and 16% from base case, respectively. Lowering the AE temperature setpoint is expected to have a significant effect on the performance and costs of GHP + AE in cool climatic regions because it reduces the potential and frequency of using AEs in combination with GHPs. Compared to Caribou, the effects of lowering the AE temperature setpoint in Florida are marginal because of the high cooling-load of the region.

When the AE temperature setpoint increases to 15 °C, the performance of the GHP + AE system in Caribou results in a COP increase of nearly 16%, and a decrease in LEC/LCO_2e emissions and TCO by over 40% and 12% from base case, respectively. In Florida, an increase of the AE temperature setpoint results in a marginal increase of the GHP + AE system performance and cost reduction. Specifically, the COP increases by nearly 1%, and the LEC/LCO$_2$e emissions and TCO decrease by almost 5% and over 1% from base case, respectively. Even with a 50% increase in the AE temperature setpoint, weather boundaries located in warm climates may not benefit from installing hybrid GHP systems because the added CAP costs does not result in a significant decrease of LOM costs.

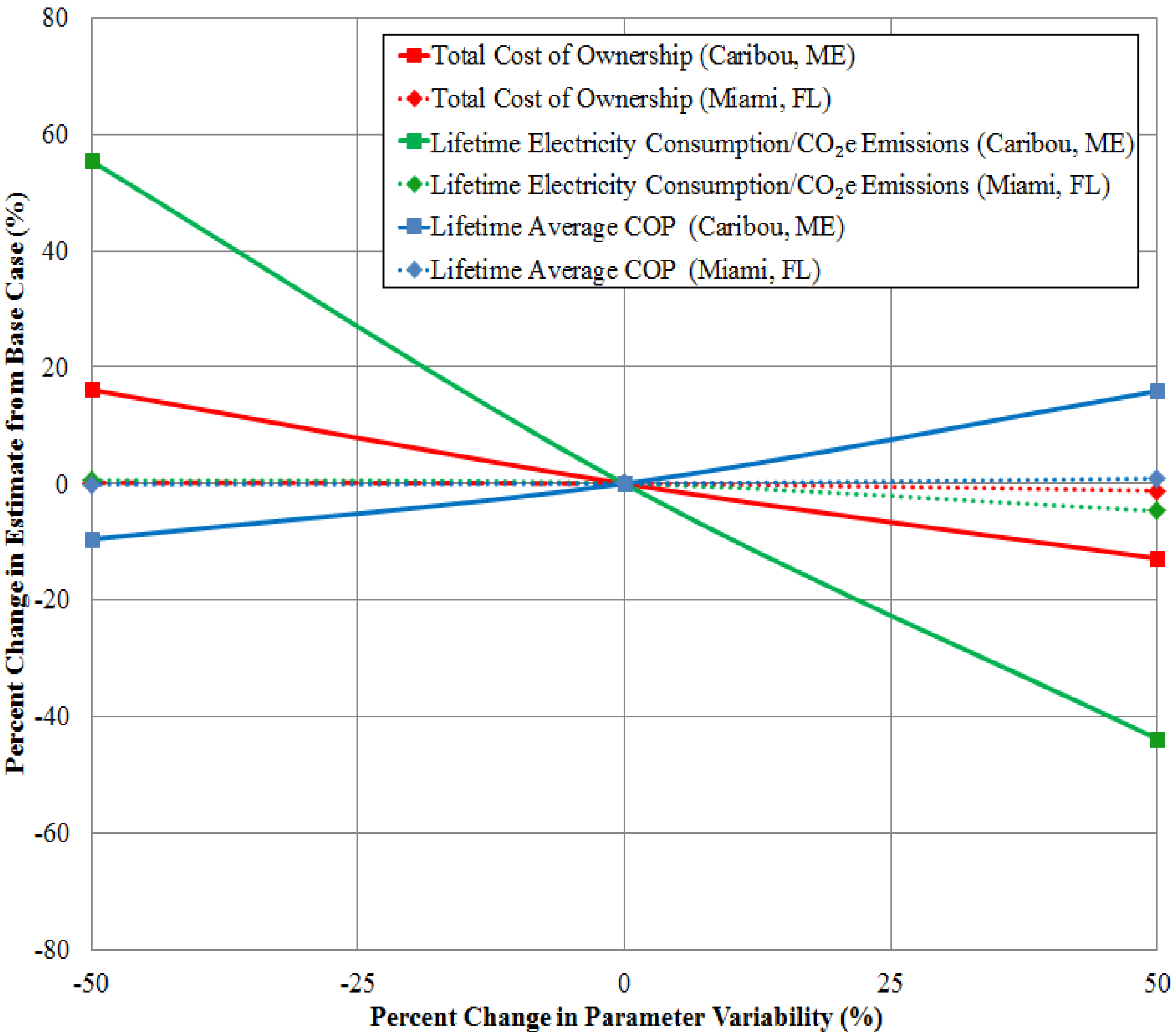

Figure 4.39 – Air Economizer (AE) temperature setpoint sensitivity analysis for case 2 (GHP + AE) in Caribou, ME and Miami, FL.

Case 5: TEEP Sensitivity Analysis for Minneapolis, MN and Sacramento, CA

For case 5, the TEEP impacts of variations in the AE temperature setpoint for Minneapolis and Sacramento is provided in Figure 4.40. Similar to case 2, a decrease of the AE temperature setpoint to 5 °C from base case (10 °C) results in an increase of the LEC/LCO_2e emissions and TCO by over 20% and 9%, respectively, for both weather boundaries. Increasing the AE temperature setpoint to 15 °C from base case reduces the LEC/LCO_2e emissions and TCO by over 20% and 8%, respectively, for both Minneapolis and Sacramento. For case 5, variations in the AE setpoint temperature in Sacramento (climatic region D) significantly affects the performance and costs of the system.

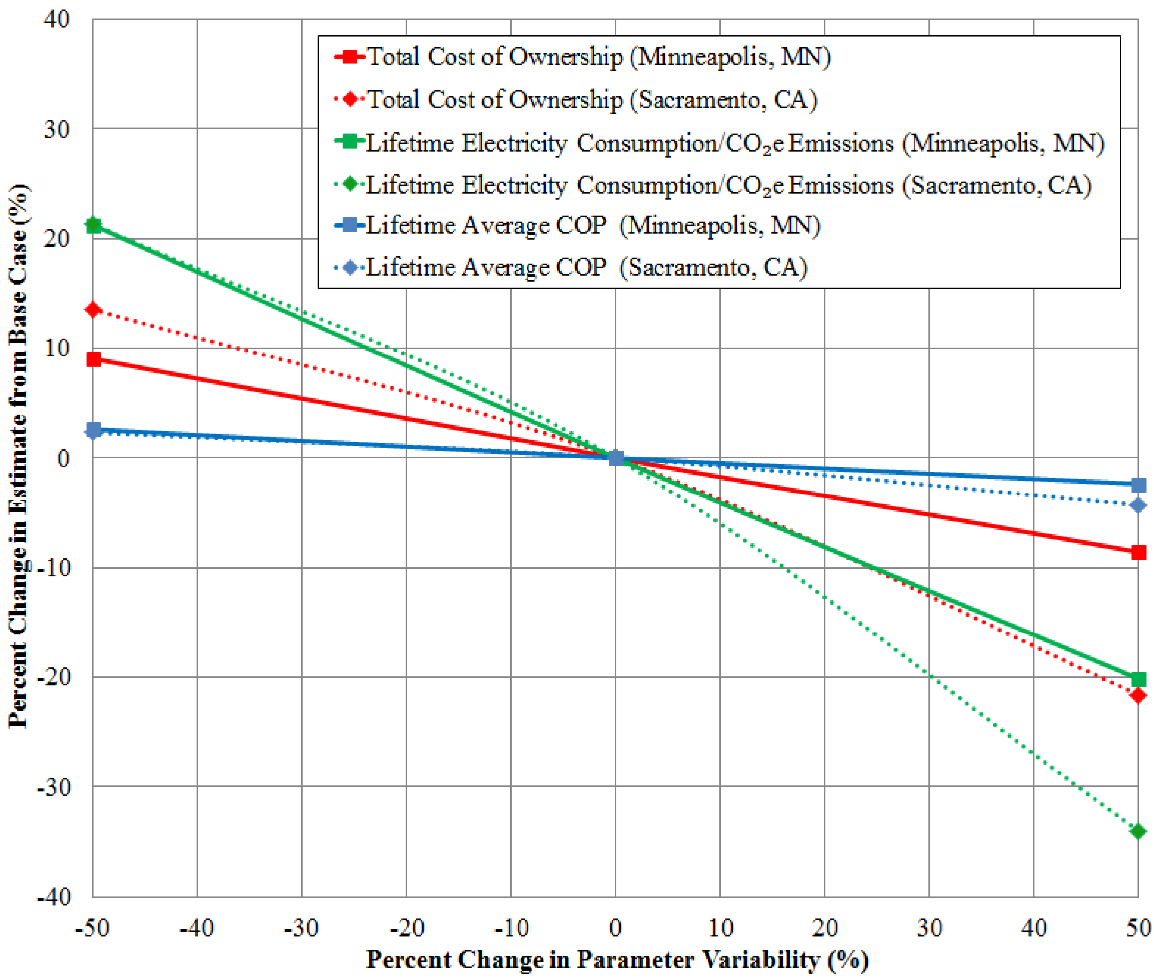

Figure 4.40 – Air Economizer (AE) temperature setpoint sensitivity analysis for case 5 (ASHP + AE) in Minneapolis, MN and Sacramento, CA.

4.4.2: TCO Sensitivity Analysis of Hybrid GHP and ASHP Systems from Variations in Financial Parameters

In this section, the sensitivity analysis of hybrid GHP and ASHP systems consider variations in financial parameters that include unit capital expenditure, drilling costs, operating costs (electricity rates), installation costs, maintenance costs, and incentives (see Table 4.16 in Section 4.4). For each parameter, the sensitivity analysis considers the effect of financial variability in the TCO for one cooling configuration in six geographic locations. Summary results of the TCO sensitivity analyses for all five cooling configurations in six geographic locations are provided in tables A.19 – A.47 of Appendix A.

Unit Capital Expenditure

For all cooling configurations, the sensitivity analysis evaluates the effect in the TCO from variations of ± 10% and ± 50% in the unit capital expenditure of GHP, ASHP, AE, and DC units from base case scenario. In this section, the TCO sensitivity analysis from variations in the unit capital expenditure is provided for case 2 (GHP + AE) in Minneapolis, MN.

Case 2: TCO Sensitivity Analysis for Minneapolis, MN

In Figure 4.41, the TCO sensitivity to unit capital expenditure variations of ± 10% and ± 50% in Minneapolis is presented. A ± 10% change in the unit capital expenditure of the GHP + AE system from base case has a marginal effect of roughly 3% in the TCO of the system. However, if the unit capital expenditure decreased by at least 50%, the TCO of the GHP + AE system would decrease by over 14% from base case. Nationwide deployment of GHP + AE systems for cooling cellular tower shelters may benefit from reductions in the unit capital expenditure from economies of scale resulting in attractive TCO reductions. From Figure 4.41, unit capital expenditure in Minneapolis is the most sensitive cost parameter followed closely by the operating and drilling costs. The least sensitive parameter is the installation costs. Furthermore, if incentives of 10% and 50% on GHP technology were available, the TCO of the system would decrease by 6% and 30% from base case, respectively.

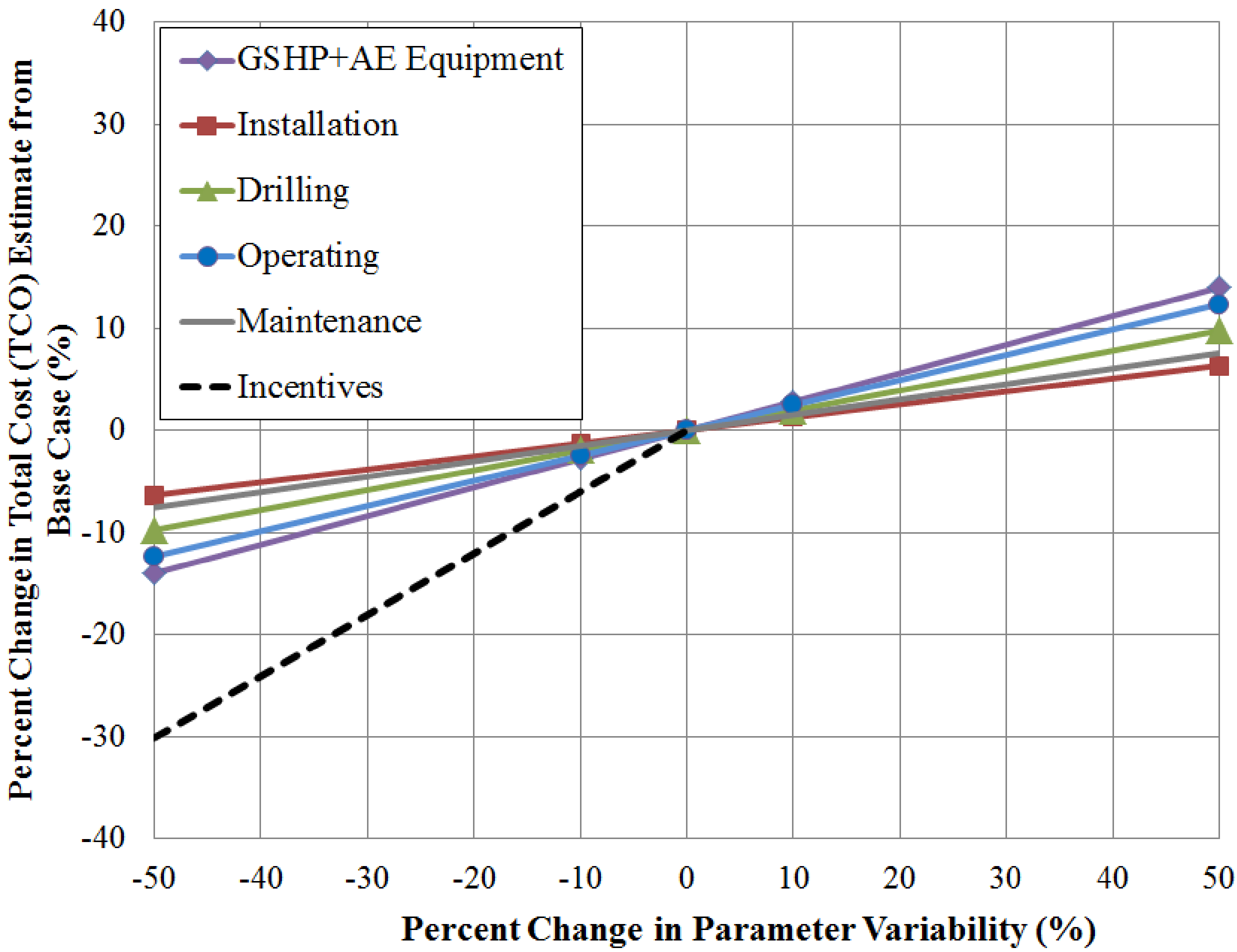

Figure 4.41 – Unit capital expenditure sensitivity analysis for case 2 (GHP + AE) in Minneapolis, MN.

Drilling Costs

For cases considering GHP systems (cases 1 – 3), the sensitivity analysis evaluates the effect in the TCO from ± 10% and ± 50% variations in the drilling costs from base case scenario. For the drilling cost variations, the TCO sensitivity analysis is provided for case 1 (GHP-only) in Miami, FL.

Case 1: TCO Sensitivity Analysis for Miami, FL

In Figure 4.42, the TCO sensitivity to drilling cost variations of ± 10% and ± 50% in Miami is presented. A 10% and 50% increase in the drilling costs increases the TCO by over 5% and 27% from base case, respectively. From the six geographic locations discussed in Section 4.3, Miami results in the highest TCO, CAP costs, and LEC because the BHE installation field exceeds 1,000 m of total BHE length. Therefore, changes in the drilling costs result in the most sensitive parameter in the TCO, followed by the operating costs from electricity purchases to operate GHP systems. For cooling-dominated applications in warm climates, reductions in the drilling costs and incentives consideration will make GHP systems more attractive. From Figure 4.42, the least sensitive parameters in the TCO are the maintenance and installation costs.

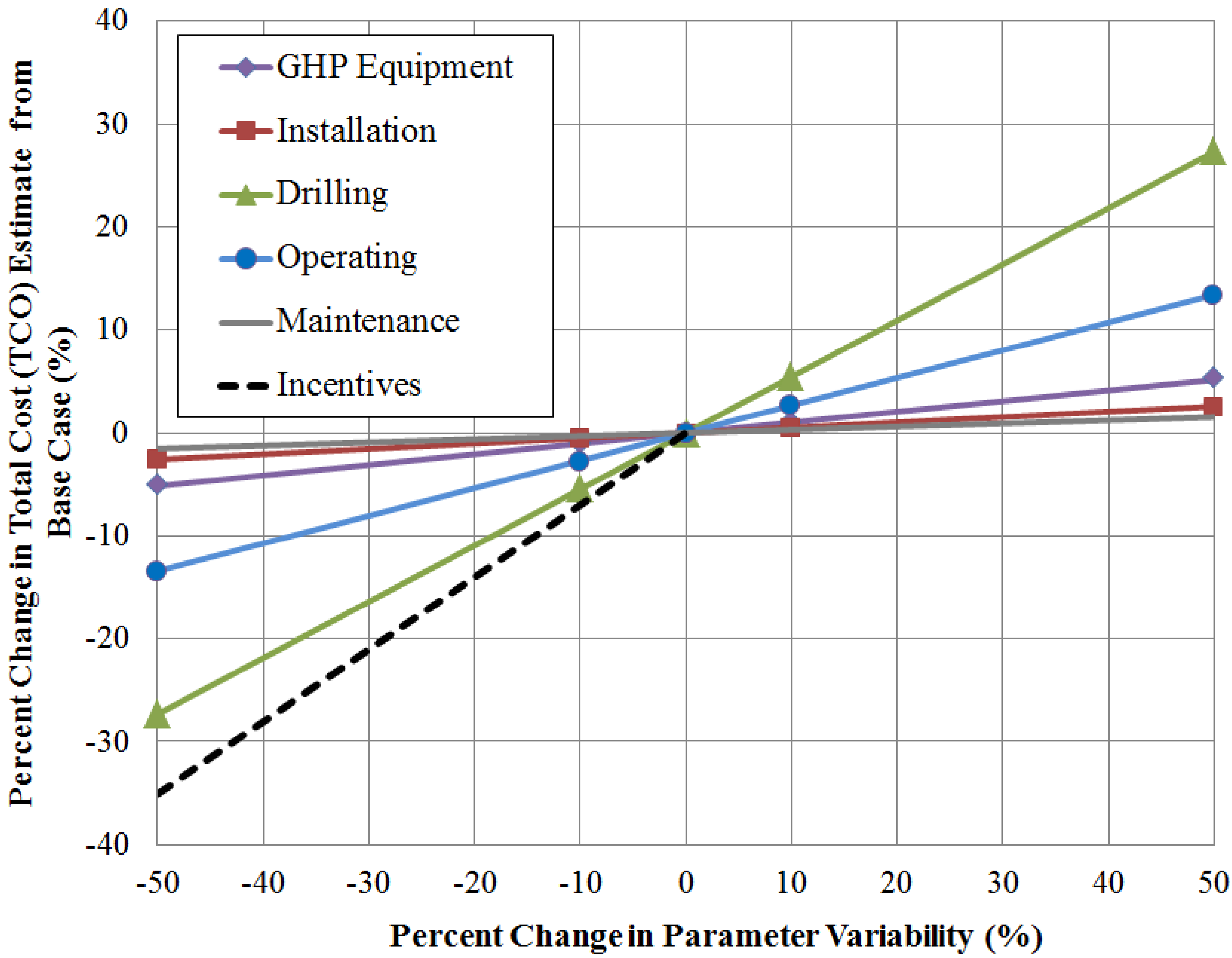

Figure 4.42 – Drilling cost sensitivity analysis for case 1 (GHP-only) in Miami, FL.

Operating Costs (Electricity Rates)

For all cooling configurations, the sensitivity analysis evaluates the TCO performance from ± 10% and ± 50% variations in the operating costs from changes in the electricity rates. The TCO sensitivity analysis from electricity rates variability is provided for case 4 (ASHP-only) in Varna, NY.

Case 4: TCO Sensitivity Analysis for Varna, NY

In Figure 4.43, the TCO sensitivity from ± 10% and ± 50% variations in the electricity rates for ASHP systems in Varna is presented. A 10% increase in the base case electricity rates to operate ASHP systems increases the TCO by over 6%. Furthermore, if the electricity rates increase by 50%, the TCO for the Varna site increases by over 34% from base case. TCO includes the CAP and LOM costs to operate and maintain the system throughout its lifetime. The variability of electricity prices over the years and the efficiencies of the cooling configurations in place are expected to significantly impact the LOM costs of all cooling configurations, especially in states with high electricity prices.

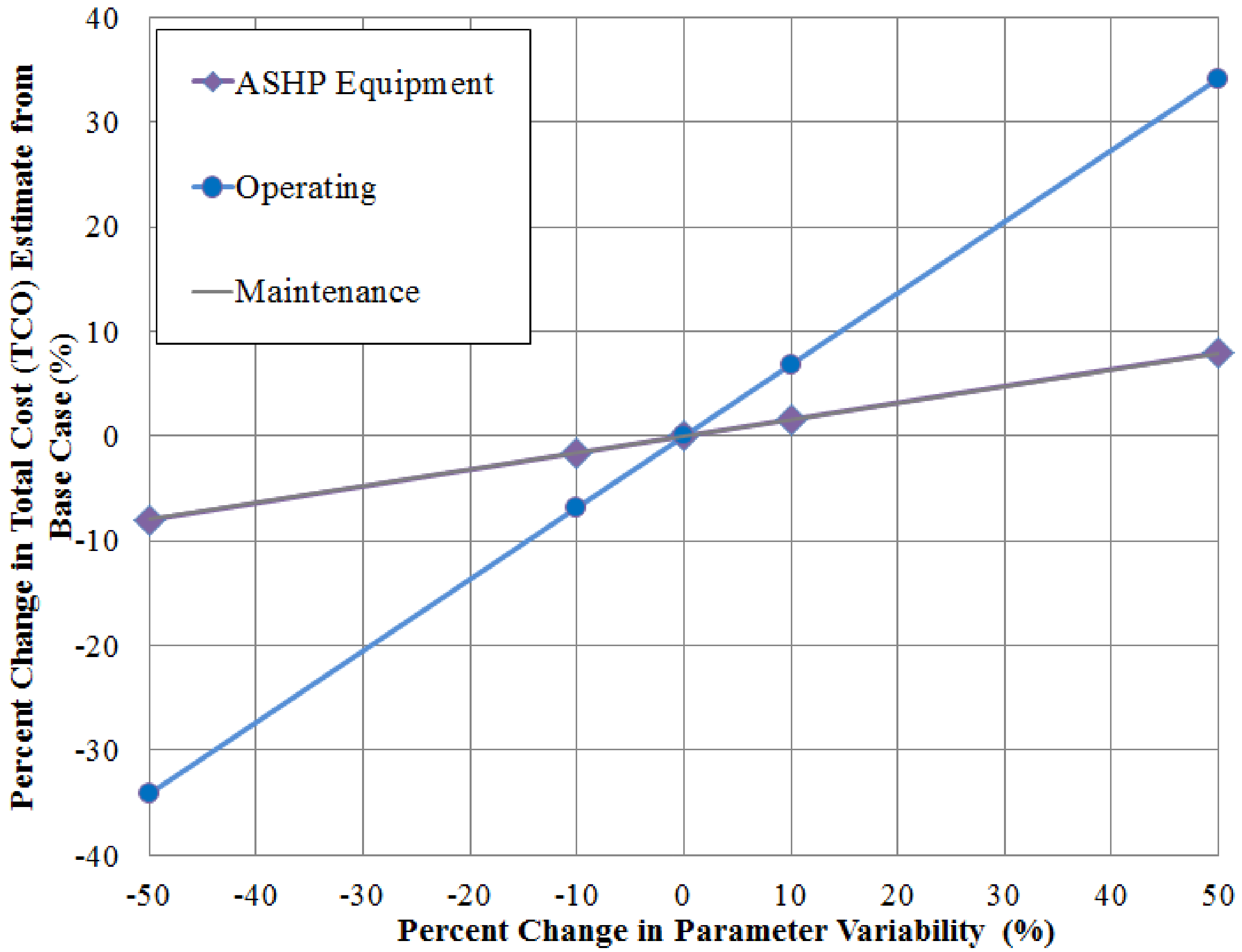

Figure 4.43 – Operating cost (electricity rates) sensitivity analysis for case 4 (ASHP-only) in Varna, NY.

Installation Costs

For cases considering GHP systems (cases 1 – 3), the sensitivity analysis evaluates the TCO effects from variations in the installation costs of the system, including pumps and piping. Specifically, the TCO performance from ± 10% and ± 50% variations in the base case installation cost is assessed. For the installation cost variation, the sensitivity analysis is provided for case 3 (GHP + DC) in Denver, CO.

Case 3: TCO Sensitivity Analysis for Denver, CO

For cases 1 – 3 across all six geographic locations, variations in the installation costs of GHP systems have a minimal influence in the TCO. From Figure 4.44, a ± 10% change in the base case installation costs of hybrid GHPs in Denver has a marginal effect of roughly 1% on the TCO of the system. Furthermore, a ± 50% change in the installation costs varies the TCO by roughly 5% from base case. From Figure 4.44, the parameters that least affect the TCO in Denver include maintenance and installation costs. The parameters that are highly sensitivity in the TCO include operating costs and incentives, followed by the unit capital expenditure.

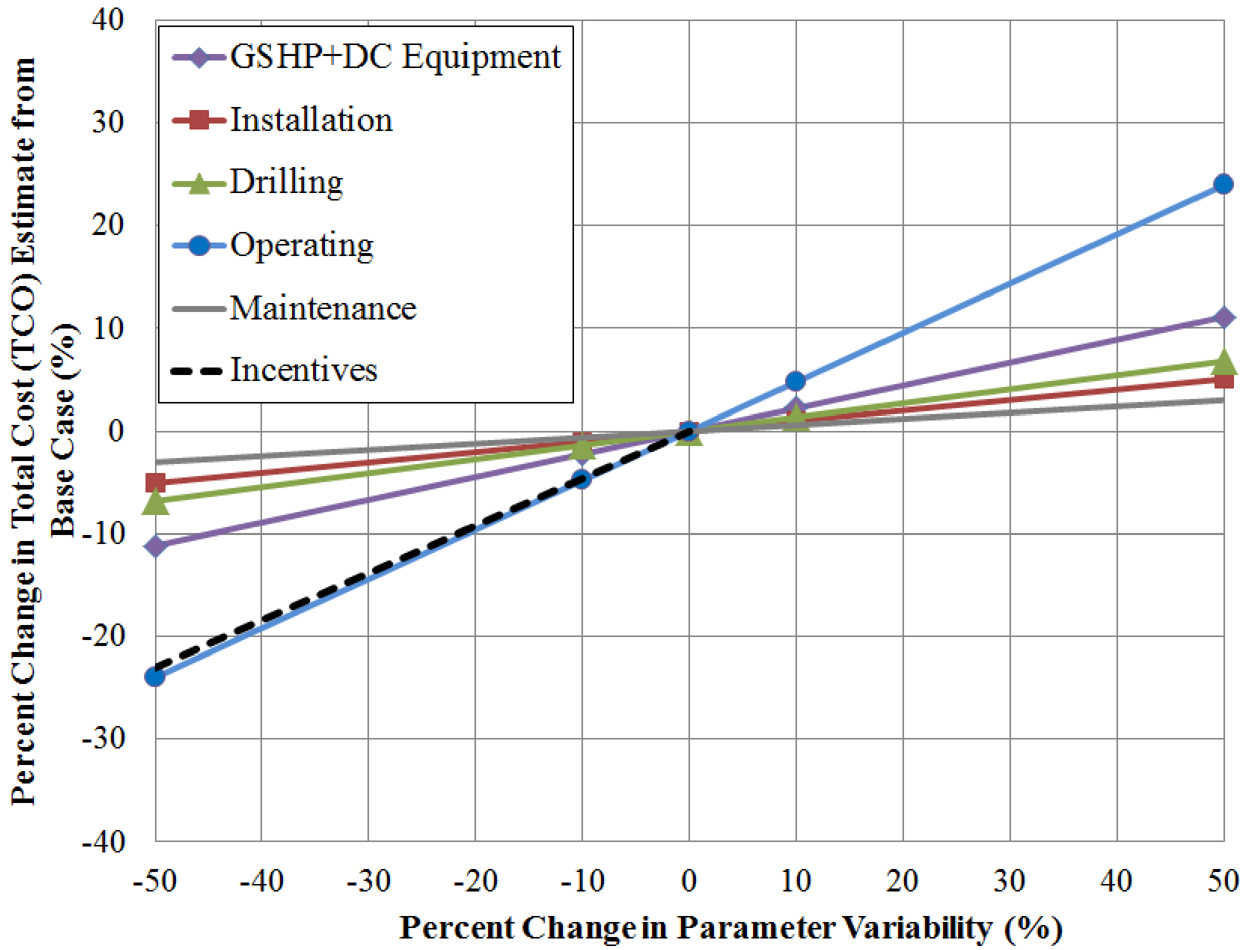

Figure 4.44 – Installation cost sensitivity analysis for case 3 (GHP + DC) in Denver, CO.

Maintenance Costs

For all cooling configurations, the sensitivity analysis evaluates the TCO performance from ± 10% and ± 50% variations in the base case maintenance costs of GHP, ASHP, and AE systems. For the maintenance cost variations, the sensitivity analysis is provided for case 5 (ASHP + AE) in Caribou, ME.

Case 5: TCO Sensitivity Analysis for Caribou, ME

In Figure 4.45, the TCO sensitivity from variations of ± 10% and ± 50% in the maintenance costs for ASHP + AE systems in Caribou is presented. A 10% and 50% increase in the base case maintenance costs increases the TCO by over 3% and 16%, respectively. The ASHP and AE units incur higher annual maintenance costs than GHP systems. From Table 4.8 in Section 4.3, ASHP and AE units incur an annual maintenance cost of $580/year and $200/year, respectively. The annual maintenance of GHP systems is around $200/year. From Figure 4.45, the TCO in Caribou is the most sensitive to operating costs, followed closely by maintenance costs and the ASHP + AE unit equipment.

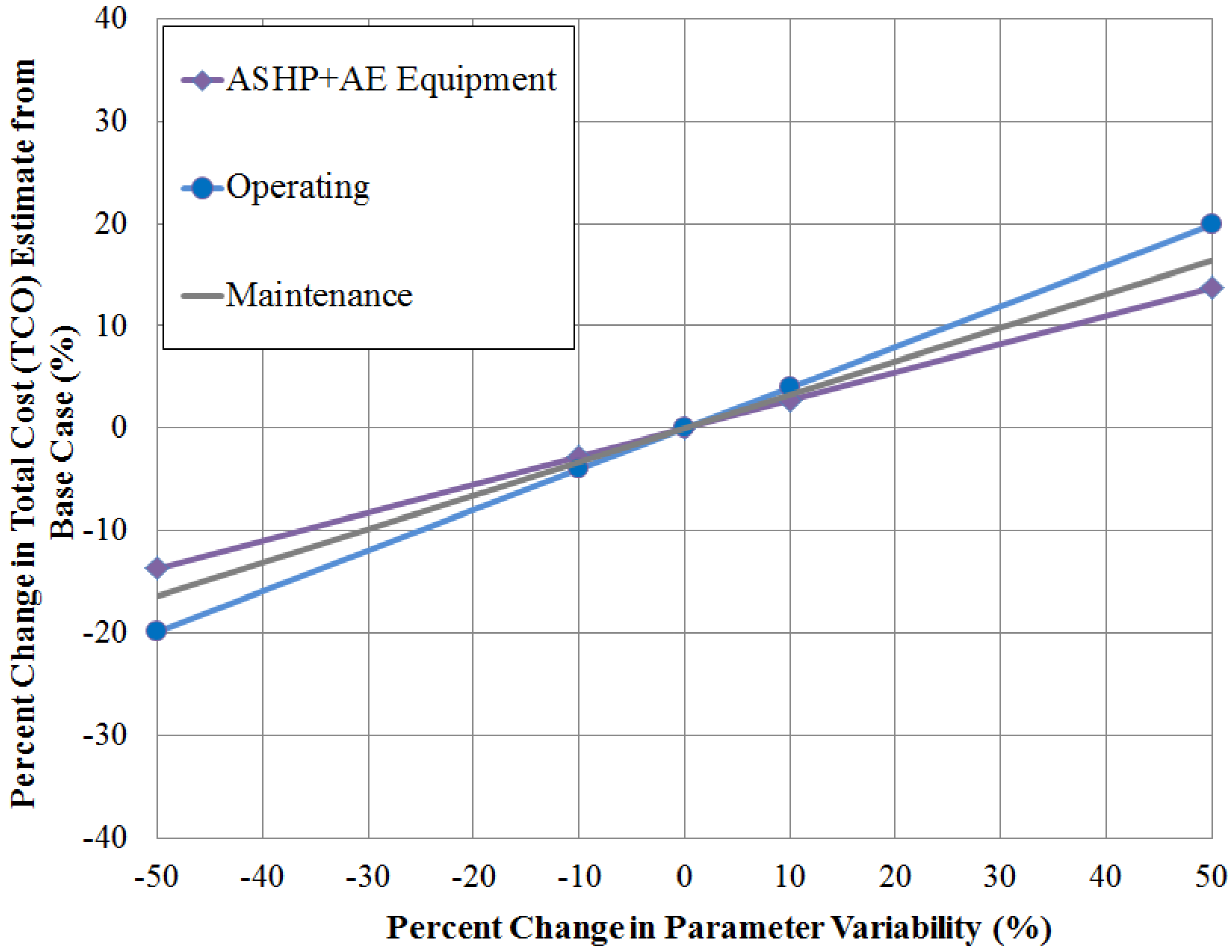

Figure 4.45 – Maintenance cost sensitivity analysis for case 5 (ASHP + AE) in Caribou, ME.

Incentives

For cases considering GHP systems (cases 1 – 3), the sensitivity analysis evaluates TCO performance from potential sources of incentives, rebates, and grants that could favor the implementation of GHP system in commercial installations. In this case study, incentives are considered for case 1 (GHP-only) in Sacramento, CA.

Case 1: TCO Sensitivity Analysis for Sacramento, CA

In Figure 4.46, the TCO sensitivity from implementing incentives on the CAP costs of GHP systems is presented. A 10% incentive on the CAP costs decreases the TCO of the GHP system by over 4% from base case. Furthermore, if incentives in the amount of 50% were available, the TCO of the GHP system would decrease by over 23% from base case. From Figure 4.43, the TCO in Sacramento is the most sensitive to operating costs; however, the TCO is nearly as sensitive to incentives as operating costs.

Historically, federal incentives for commercial applications have included a Business Energy Investment Tax Credit of 10% for spending on energy-efficient property in service through the end of 2016. However, incentives and rebates have varied from year-to-year. It is recommended to search for any relevant opportunities in the sources provided in Section 4.2.5 before considering installation of energy-efficient systems.

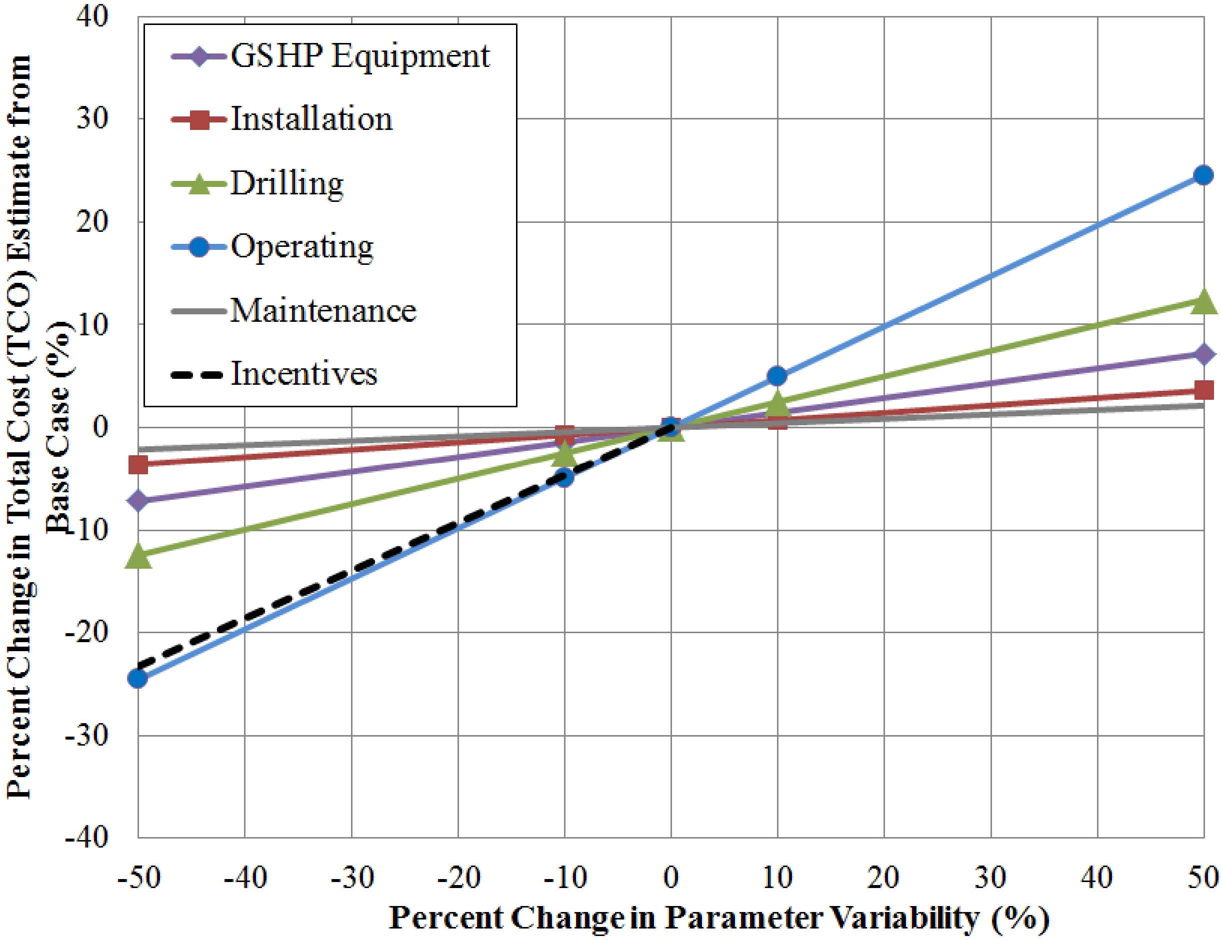

Figure 4.46 – Incentives sensitivity analysis for case 1 (GHP) in Sacramento, CA.

4.4.3: Summary and Major Findings

In this section, a TEEP sensitivity analysis of hybrid GHP and ASHP systems from variations in technical and financial parameters was conducted. For technical parameters, a one-at-a-time sensitivity analysis considered variations in the total BHE length, estimated $K_{f,s}$, and AE temperature setpoint. The financial parameters considered variations in the CAP and O&M costs, and consideration of incentives for energy-efficient technologies.

For cooling-dominated applications, the TEEP impacts of increasing the total BHE length for GHP cases in cooler climates (regions A and B) results more favorable than in warmer climates (regions D and E). In cool climates, the GHP system performance (COP) increases, resulting in lower LEC/LCO$_2$e emissions, when the total BHE length of the system is increased. In addition, LOM cost reductions surpass additional CAP costs from drilling operations in regions with cool climates (e.g., Caribou, Varna, Minneapolis) resulting in lower TCO. In warm climates (e.g., Sacramento, Miami), increases in the total BHE length result in marginal increases in the GHP COP, but significantly increases in the TCO from drilling operations of large BHE fields.

Similarly, the TEEP impacts of variations in the $K_{f,s}$ significantly affects the performance and costs for weather boundaries located in cool climates. Weather boundaries located in climatic regions A, B, and C experience significant reductions in the GHP COP (over 40% from base case) when the $K_{f,s}$ estimate is lower than the base case estimate. Likewise, when the $K_{f,s}$ value is higher than the base case estimate, increases in the COP result in reductions in the LEC/LCO$_2$e emissions and TCO. Changes in the BHE thermal field properties in cool climatic regions are likely to significantly affect the performance and costs of GHP systems. On the other hand, warm climatic regions involve large BHE field size installations; therefore, changes in the BHE thermal field properties have less of an effect on the overall performance and costs at these sites.

The TEEP sensitivity to variations in the AE temperature setpoint for cases 2 (GHP + AE) and 5 (ASHP + AE) result in an increase of the LEC/LCO$_2$e emissions and TCO when the temperature setpoint is lower than the base case temperature of 10°C. With the exception of Miami, most of the weather boundaries for case 2 experience a decrease in the system performance resulting in higher LEC/LCO$_2$e emissions and TCO from base case when the AE temperature setpoint is lowered.

For case 2 in most climatic regions, increasing the AE temperature setpoint from the base case scenario reduces LEC/LCO$_2$e emissions and TCO. Lowering or increasing the AE temperature setpoint in warm climatic regions (e.g., Miami) results in marginal effects on the performance and costs of hybrid GHP systems because of the high cooling-load of the region. As opposed to Miami, variations in the AE temperature setpoint for case 5 in Sacramento (climatic region D) significantly affect the performance and costs of the system.

For variations in the financial input parameters, the sensitivity analysis considers the TCO effects of a ± 10% and ± 50% variability in the CAP and O&M costs for each cooling configuration nationwide. A small (± 10%) and large (± 50%) variability in the model inputs were considered in order to assess the local linearity and magnitude of impact in the output of the model (TCO). In this study, the TCO was found to be essentially directly proportional (linear) to variations in the financial input parameters. For well-behaved functions, such as the financial performance metric (TCO) in this study, a one-at-a-time sensitivity analysis may be used to assess the magnitude of impact in the model output from variability in the model input parameters.

To estimate solutions to initial value problems, the Taylor series approximation may be used to assess the linear sensitivities of a function with respect to the input parameters. The Taylor polynomial series approximates the value of a function by summation of all the derivatives of that function (Miletics and Molnárka, 2004). For second-order Taylor series, the curvature (second derivative) of the line approximated at the origin of the function is negligible, as it approximates the derivative of the first-order Taylor series. Therefore, the Taylor polynomial series serves as a good local linear approximation to estimate the sensitivity of well-behaved functions.

From the six geographic locations analyzed, variability in the hybrid GHP unit capital expenditure appears highly sensitive in the TCO of Minneapolis, followed by operating and drilling costs. For drilling cost variability, the TCO sensitivity is the highest in Miami because the BHE field is the largest of all locations sampled. For cooling-dominated applications in warm climates (e.g., Miami), reductions in the drilling costs and consideration of incentives will make GHP systems more attractive.

For operating cost variability, the TCO sensitivity is high in regions with coupled high LEC and electricity rates. Therefore, the efficiencies of the cooling configurations are expected to significantly influence the LOM costs, especially in states with high electricity prices. Installation and maintenance costs of GHP systems appear to have the least effect in the TCO of the systems for all geographic locations. However, ASHP systems incur a higher annual maintenance cost than GHP systems; therefore, significant increases in the annual maintenance of ASHPs are likely to result in higher TCOs. If nationwide deployment of hybrid GHP systems occurs and incentives on energy-efficient technology are available, reductions in the unit capital expenditure are possible from economies of scale increasing the overall attractiveness of installing GHP systems.

4.5: Conclusions and Recommendations

This chapter introduced a systems engineering model (SEM) to assess the technical, economic, and environmental performance (TEEP) of hybrid geothermal heat pump (GHP) and air-source heat pump (ASHP) systems for cooling of cellular tower shelters nationwide. The SEM considers the TEEP of GHPs in combination with air-side economizers (AE) or dry-coolers

(DC) and ASHP in combination with AE systems. In this chapter, five cooling configurations were evaluated: 1) GHP-only; 2) GHP + AE; 3) GHP + DC; 4) ASHP-only; and 5) ASHP + AE. Furthermore, a sensitivity analysis assessed the influence on the TEEP of the cooling configurations from variability in technical and financial parameters.

To enable a TEEP comparison of hybrid GHP and ASHP systems nationwide, the SEM was developed as a multidisciplinary framework that incorporates spatial, technical, and economic modeling. For the five cooling configurations, the SEM output involved nationwide comparison of the total cost of ownership (TCO), lifetime (20 years) electricity consumption (LEC), and lifetime CO_2-equivalent emissions (LCO_2e). The TEEP performances for all case studies were calculated and summarized based on climatic regions from the annual mean surface temperature of TMY3 weather boundaries (areas) (see Figure 4.3 in Section 4.2). Weather boundaries with cooler climates are located in regions A, B, and C, and boundaries with warmer climates include regions D and E.

A summary of the TCO for all cooling configurations based on climatic regions is presented in Table 4.17. For all geothermal cases (cases 1 – 3), the size of the borehole heat exchanger (BHE) field affects the TCO, which includes the capital and lifetime operating and maintenance costs. Weather boundaries located in cool climates result in low TCO because of small BHE fields (under 270 m in some regions). Correspondingly, warm climatic regions result in high TCO because of large BHE fields, over 1,000 m of total length for some regions.

For case 2 (GHP + AE), the use of AE benefit weather boundaries located in regions A, B, and C because cool air is allowed to flow into the shelter reducing the cooling demand in the GHP system. In contrast, the benefits of using AE units in regions D and E are lower because warm temperatures reduce the potential use and frequency of hybrid GHP systems. For case 3 (GHP + DC), coupling the GHP system with DC units in all climatic regions results in a decrease of the BHE field compared to case 1. The DC unit allows the BHE field to thermally recover while actively cooling the shelter.

Case 4 (ASHP-only) represents the business-as-usual (BAU) scenario for cooling cell tower shelters nationwide, and case 5 (ASHP + AE) represents a hybrid option to the current BAU case. Similarly to case 2, the use of AE units in case 5 benefit cool climatic regions the most because cool air flowing into the shelter reduces the load in the ASHP. When the cooling load in the ASHP is reduced, less electricity is consumed, lower CO_2e emissions are released, and lower operating costs result.

Table 4.17 – Summary of the Total Cost of Ownership for all cooling configurations based on climatic regions.

	Total Cost of Ownership ($)				
Cooling Configuration	**Climatic Region A**	**Climatic Region B**	**Climatic Region C**	**Climatic Region D**	**Climatic Region E**
Case 1: GHP-only	$45,000 - $56,100	$42,000 - $67,700	$45,800 - $83,500	$52,100 - $87,400	$67,500 - $96,900
Case 2: GHP + AE	$29,200 - $38,500	$33,400 - $50,800	$39,200 - $67,200	$48,400 - $86,500	$68,300 - $100,700
Case 3: GHP + DC	$42,900 - $57,100	$40,400 - $70,100	$42,600 - $71,200	$49,200 - $71,200	$66,400 - $84,300
Case 4: ASHP-only (BAU)	$39,500 - $52,200	$39,100 - $63,400	$39,800 - $65,100	$42,600 - $68,000	$46,100 - $71,300
Case 5: ASHP + AE	$25,800 - $35,400	$27,700 - $46,400	$32,700 - $62,900	$39,600 - $68,700	$46,900 - $73,700

The configuration with the lowest overall TCO is case 5 (ASHP + AE), followed by case 2 (GHP + AE). The configuration with the highest overall TCO is case 1 (GHP-only), followed closely by case 3 (GHP + DC) and case 4 (ASHP-only). Furthermore, the configuration with the lowest LEC/LCO$_2$e emissions is case 2, and the highest is case 4.

The TEEP sensitivity analysis presented in this chapter considered one-at-a-time variations of technical and financial parameters across six geographic locations nationwide for all five cooling configurations. For GHP cases, major findings show that the TEEP impacts of increasing the total BHE length in cooler climates is more favorable than in warmer climates because of improved GHP system performance (COP) resulting in a TCO reduction. Similarly, the TEEP impacts of variations in the $K_{f,s}$ affects the performance and costs of weather boundaries located in cool climates the most.

For the TCO sensitivity of financial parameters, the drilling cost variability was significant in regions with large BHE fields (e.g., Florida), and minimal in regions with small BHE fields (e.g., Maine). For cooling-dominated applications in warm climates, reductions in the drilling costs will make GHP systems more attractive. For operating cost variability, the TCO sensitivity is high in regions with coupled high LEC and electricity rates (e.g., California).

The base case results presented in this study provide an approximation of the performance of five configurations for cooling of cellular tower shelters nationwide. To increase the accuracy and the spatial resolution at a particular location, it is recommended to perform a detailed climatic and hydrogeological analysis. For instance, the TMY3 weather dataset employed in the analysis represents typical rather than extreme weather conditions. Therefore, the design of the hybrid GHP and ASHP systems provided in this study are not representative of peak load conditions and/or worst-case scenarios.

Furthermore, the nationwide hydrogeological characterization of GHP systems presented in this study represents first-order approximations of the site thermal properties. To increase the characterization of site-specific BHE fields, thermal response tests (TRT) and laboratory measurements on individual boreholes should be performed prior to the design of GHP systems. It is expected that GHP systems installed under the presence of groundwater flow may result in capital and operational cost reductions from improved system performance because groundwater flow enhances heat dissipation.

With the use of energy-efficient GHP systems, regions with high electricity prices and electricity consumption will experience lower costs and environmental impacts from a reduction in operating conditions over the lifetime of the system (20 years). If incentives are considered in the base case scenario, large reductions in the TCO are observed, increasing the attractiveness of implementing GHP systems.

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PART II:

INTRODUCTION TO SHALLOW GEOTHERMAL DISTRICT ENERGY SYSTEMS FOR SUSTAINABLE NEIGHBORHOOD DEVELOPMENT

Chapter 5: Shallow Geothermal District Energy Systems for Sustainable Neighborhood Development

CHAPTER 5

SHALLOW GEOTHERMAL DISTRICT ENERGY SYSTEMS FOR SUSTAINABLE NEIGHBORHOOD DEVELOPMENT

5.1: Introduction to District Energy Systems

District energy systems can provide space heating, cooling, and domestic hot water to a community by distributing thermal energy from a centralized location through a network of pipes. The thermal energy may be in the form of steam, hot water, or chilled water produced from fossil fuels or from renewable energy sources (ASHRAE, 2000; King, 2012). The focus of this chapter is restricted to district energy systems primarily from geothermal energy sources.

The three main components of district energy systems include: 1) Energy production; 2) Energy distribution; and 3) Energy consumption. In Figure 5.1, the energy production component may include thermal energy produced from a geothermal resource, boiler, or incinerator (ASHRAE, 2000). Thermal energy from geothermal resources may be supplied directly from natural hydrothermal convection systems, from non-hydrothermal hot dry rocks (enhanced geothermal systems), or by using shallow geothermal (ground-source) heat pump (GHP) systems (Rafferty, 1990; Tester et al., 2012).

The heat central is a building adjacent to the energy production system that houses heat pumps and auxiliary boilers connected to the pipes in the distribution system. The auxiliary boilers may be used to cover a certain percentage of the annual peak load of the area. For instance, geothermal district energy systems are often designed to cover between 50 – 70% of the annual peak load. Designing a geothermal system to cover 100% of the peak heating load does not result economically viable because the system may be overdesigned to cover peak demand that occurs only around 3 – 5% of the time in a given year (Bloomquist, 2003; Boyd, 2009; Chatenay et al., 2014).

The energy distribution system consists of a set of insulated supply and return pipes that carry the thermal energy to the end users. The insulated supply and return pipes may be buried directly in the ground or placed in a concrete tunnel. The energy consumption system involves building equipment that may include heat pumps, heat exchangers, or radiator systems that supply the space heating, cooling, or domestic hot water from the energy production and distribution systems (ASHRAE, 2000; Chatenay et al., 2014).

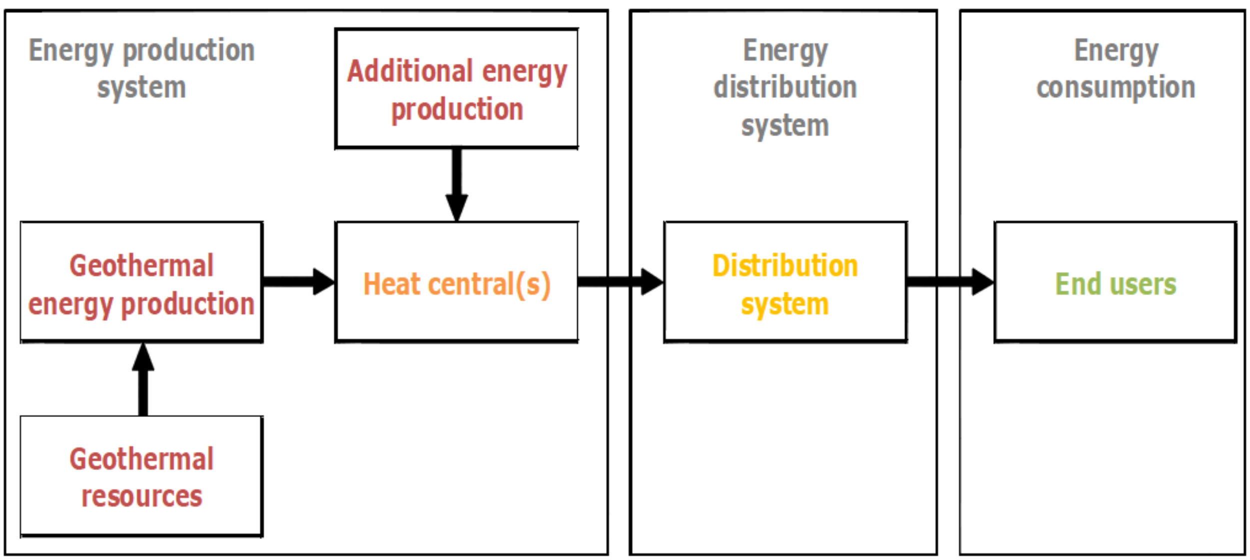

Figure 5.1 – Three main components of district energy systems (Chatenay et al., 2014).

The application of district energy systems are attractive in regions of high population density and high thermal demand (King, 2012). According to Ulloa (2007), the U.S. has over 5,000 steam-based district energy systems providing over 300 million MWh of thermal energy. The Con Edison Steam district heating system in New York City is the largest commercial system in the U.S., providing service to more than 3 million customers (conEdision, 2016). Some of the benefits of installing district energy systems include moderate investment costs, low operating and maintenance costs, flexibility in the fuels used for energy production, low environmental emissions, and increased consumer comfort (ASHRAE, 2000).

5.2: Potential for Shallow Geothermal District Energy Systems in Small Communities

Currently, there are over 18 geothermal district heating (GDH) systems in the U.S., mostly located in Western states. About 90% of the U.S. GDH systems have been developed since the 1970s and are still in operation. The Warm Springs Water District system in Boise, Idaho is the oldest GDH system in the U.S., and has been in operation since the 1890s. The Western U.S. GDH resource characteristic consists of natural hydrothermal convection systems with water temperatures in the range of 58 – 103 °C (138 – 218 °F) at depths ranging from 83 – 923 m (275 – 3,030 ft.) (Rafferty, 1990; Lund, 1999).

More recently, shallow geothermal (ground-source) district energy systems (GSDE) have gained popularity in college campuses and municipalities in the Midwestern and Northeast U.S. In 1994, Stockton College in New Jersey installed a GSDE system to supply space heating and cooling to 14 academic buildings. The geothermal system consists of 400 wells, each drilled to a depth of 425 feet, located under a 4-acre parking lot. The net installed cost of the GSDE system was over $4 million dollars with a payback period of around 3.5 years (Taylor et al., 1997; Stockton, 2010).

In 2012, Ball State University (BSU) in Indiana installed one of the nation's largest GSDE systems to provide for heating and cooling to 47 buildings on campus. The system consists of 3,600 wells, each ranging in depths from 400 – 500 feet, and includes two energy stations that house a large heat pump chiller and two water supply lines (Mahlmann and

Escobedo, 2012; BSU, 2017). BSU estimates the capital expenditure costs to be in the range of $70 - $75 million dollars with a payback period of around 7.5 years (Mahlmann and Escobedo, 2012; BSU, 2017).

In a community of West Union, Iowa, a GSDE system was installed to provide for heating and cooling to about 60 businesses in a three-block area. The GSDE consists of 132 wells, each drilled to a depth of 300 feet. The capital expenditure of the system was around $2 million dollars, and was mostly covered by federal grants from the Department of Energy and the Environmental Protection Agency (Geerts, 2013; Midwest Energy News, 2014).

In small-to-mid-size communities, GSDE systems may be part of the strategic planning to sustainably transform and revitalize neighborhoods. Installation of community-scale GSDE systems may be possible in municipal parking lots and/or vacant areas. An underground shallow geothermal field (depths less than 150 m or 500 ft.) may be installed in open lots, and the resource shared by multiple users for space heating, cooling, and domestic hot water. GSDE systems are highly efficient systems with long expected lifetimes that exceed 20 years, and low maintenance and operating costs compared to conventional heating and cooling systems.

In Chapter 6, an integrative framework and tool for the assessment of GSDE systems at a neighborhood scale is presented. Furthermore, case studies are provided summarizing the technical and economic performance of GSDE systems in a neighborhood in Utica, NY. The work presented in Chapter 6 builds from a report by George et al. (2016) on Sustainable Development Potential in Utica’s Urban Core.

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Chapter 6: Development of the GeoDistrict Energy Tool for Sustainable Neighborhood Design

CHAPTER 6

DEVELOPMENT OF THE GEODISTRICT ENERGY TOOL FOR SUSTAINABLE NEIGHBORHOOD DESIGN

6.1: Introduction

The objectives of this chapter are to introduce an integrated framework and tool for assessment of shallow geothermal (ground-source) district energy (GSDE) systems at a neighborhood scale. Several case studies are discussed summarizing the opportunities of GSDE implementation in a neighborhood within the "Rust Belt" City of Utica, NY. In addition, this chapter covers a brief historical context of Utica's sustainability plans, and ongoing initiatives taken by our group to promote the adoption of sustainable neighborhood practices in Rust Belt cities.

For decades, Rust Belt cities in the United States have struggled with sustained economic decline and population loss as a result of changes in manufacturing practices, regional migration, and suburbanization (Mallach and Brachman, 2013). Cities that were once strong industrial and economic powerhouses have been left distressed, with empty houses, vacant lots, decaying infrastructure, and struggling families (Vey, 2007; Mallach and Brachman, 2013).

Rust Belt cities have many legacies and assets that present opportunities for revitalization and economic growth (Vey, 2007). Some of the legacies and assets that characterize Rust Belt cities include historic buildings, walkable downtowns, world-class universities and medical centers, and diverse transportation networks, among others (Mallach and Brachman, 2013). Pittsburgh, Pennsylvania is a good example of a Rust Belt City that has used its world-class universities and medical centers to diversify its economy and revitalize its neighborhoods (Vey, 2007; Mallach and Brachman, 2013). Revitalization of Rust Belt cities must involve an integrated approach that embraces economic growth, sustainable planning and development, and social justice to ensure the well-being of future generations (R2G, 2010).

In 2011, Governor Andrew Cuomo of NY announced the “Cleaner, Greener Communities Program” directed by the New York State Energy Research and Development Authority (NYSERDA) to promote regional development through sustainable planning and smart growth (Mohawk Valley, 2011). Subsequently, the Mohawk Valley Regional Sustainability Plan was produced to define goals, indicators, and targets for the social, economic, and environmental well-being of the region (Mohawk Valley, 2011; Moreno-Long, 2016). The sustainability plan includes the adoption of practices to increase renewable energy use, control regional sprawl, increase public transit and alternative modes of transportation, and restore neighborhoods (Mohawk Valley, 2011).

In addition to the Mohawk Valley Regional Sustainability Plan, several initiatives are underway in NY to assist in the sustainable revitalization of Rust Belt cities. The Rust to Green (R2G) initiative is a university-community partnership established at Cornell University to collaboratively work in identifying and designing innovative solutions for sustainable revitalization of Rust Belt cities (R2G, 2010; George et al., 2016). The R2G initiative has been active in upstate NY since 2010 and focuses on four key priorities: green economy, green buildings and infrastructure, green community development and education, and green policies. Utica’s R2G accomplishments to date include the revitalization of parks, streets, and parking lots using green practices, as well as educational and cultural events that promote sustainable neighborhood development (R2G, 2010).

Chapter 6: Development of the GeoDistrict Energy Tool for Sustainable Neighborhood Design

Utica, NY is located in Oneida County on the Mohawk Valley region and sits on the New York State Canal System between Syracuse and Albany (Reber et al., 2013). Like other Rust Belt cities in America, Utica has experienced severe economic and population decline since the 1950s. Over the past sixty-five years, Utica has lost over 38% of its population and poverty rates are up to 30% (Hevesi, 2004; R2G, 2010; Thomas, 2014). Furthermore, Utica suffers from aging infrastructure, vacant lots, and decaying neighborhoods (Moreno-Long, 2016).

Nonetheless, Utica possesses many legacies and assets and has the potential to become an innovator and incubator of sustainable community revitalization practices (R2G, 2010; Reber et al., 2013; George et al., 2016; Moreno-Long, 2016). In 2013, Governor Cuomo announced the Nano Utica initiative, which sought to invest $1.5 billion dollars to bring a "technology-based economic transformation" to the area. The creation of Nano Utica has the potential to create more than 1,000 jobs and promises to transform the region into a major hub for nanotechnology research and development (City of Utica, 2015).

In addition, the City of Utica is designated as a United Nations refugee resettlement city and has been receiving a large influx of new residents from various countries. The influx of new residents to the area has stabilized the population loss rate, and is strengthening the local economy through increases in home and business ownerships (R2G, 2010; George et al., 2016).

In 2014, a group of faculty and students at Cornell came together to design an integrated plan for sustainable neighborhood development in downtown Utica. The group includes faculty, graduate students, and undergraduate students from different departments, including Engineering and Landscape Architecture. The integrated plan provides an assessment of the area's current sustainable energy and neighborhood design practices. In addition, the plan includes the development of frameworks and tools to assess the technical and economic feasibility of integrating sustainable energy practices in downtown Utica (George et al., 2016).

The work presented in this chapter builds from a previous study on revitalizing and transforming sustainable communities in NY (Reber et al., 2013). The study by Reber et al. (2013) presents nine key elements of any sustainable community, and discusses integrative efforts in the development and redevelopment process of building sustainable communities. The nine key elements include a systems-based integration of energy, food, water, waste, urban design, transportation, buildings, business and economic development, and governance and communication. According to Reber et al. (2013), successful integration of the key elements is possible when communities are actively engaged; coalitions and teams of local leaders, stakeholders, and universities are formed; priority areas are identified and evaluated; and financial support is solicited.

This chapter covers a case study of revitalization opportunities for the City of Utica considering several key elements of developing and redeveloping sustainable communities. Specifically, opportunities for building retrofitting, renewable energy integration, and sustainable urban design within a small neighborhood in downtown Utica are discussed. The primary focus of the chapter is to provide an integrated framework and tool for the assessment of GSDE systems at a neighborhood scale, with Utica as an example.

6.2: Sustainable Neighborhood Development Methodology: A Case Study for Utica, NY

The work presented in this section is a compilation of research efforts by faculty and students at Cornell University to design a plan for sustainable neighborhood development in downtown Utica. The objectives are to develop an integrated framework that incorporates elements of energy efficiency and conservation, renewable energy, green infrastructure and new transportation alternatives, among others (George et al., 2016).

Section 6.2.1 describes the study area, the Leadership in Energy and Environmental Design for Neighborhood Development (LEED-ND) audit, the data collection and analysis process for the study area (Moreno-Long, 2016). Section 6.2.2 suggests retrofitting opportunities for residential buildings, discusses the impact of retrofitting on a building's energy consumption, and provides expected costs and payback period for retrofitting buildings in Utica (Prathibha, 2016).

Section 6.2.3 evaluates the technical and economic potential of solar photovoltaic (PV) energy for residential and commercial applications in Utica (Li, 2016; Sud, 2017). Section 6.2.4 introduces the concept of providing space heating and cooling to a neighborhood with shallow geothermal district energy (GSDE) systems. Specifically, Section 6.2.4 introduces the "GeoDistrict Energy" tool developed in Section 6.3 to assess the techno-economic performance of GSDE systems in small-to-mid-size communities.

In this chapter, a brief discussion on the methodology and results for sections 6.2.1 – 6.2.3 is provided. Additional documentation for sections 6.2.1 – 6.2.3 can be found in George et al. (2016), Li (2016), Moreno-Long (2016), Prathibha (2016), and Sud (2017). The primary focus of this chapter is on the development and application of the GeoDistrict Energy tool discussed in sections 6.2.4, 6.3, and 6.4, an effort primarily led and coordinated by the author of this dissertation.

Chapter 6: Development of the GeoDistrict Energy Tool for Sustainable Neighborhood Design

6.2.1: Study Area, LEED-ND Audit, Data Collection and Analysis

Study Area

For the case studies presented in this chapter, a multi-block neighborhood in the downtown area of Utica was analyzed. The multi-block neighborhood includes historic buildings, commercial and residential units, and several parking lots and vacant lots. The study area is part of Utica's Scenic and Historic Preservation District, and is surrounded by many downtown businesses and cultural destinations (City of Utica, 2015; George et al., 2016).

The multi-block neighborhood, shown in Figure 6.1, is located within Genesee Street, Hopper Street, South Street, and Park Avenue. The area encompasses the historic Stanley Theater and Tabernacle Baptist Church, listed under the National Register of Historic Places (U.S. DOI, 2017). The Stanley Theater and Tabernacle Church have undergone recent renovations and have abundant opportunities for growth (Stanley Theater, 2015; Tabernacle Baptist Church, 2015).

Recently, various restaurants within the study area, including the Lotus Garden and Swifty's Restaurant & Pub, have become popular local destinations. In addition, several single-family residential units have been renovated and converted to multi-family residential units (George, et al., 2016; Moreno-Long, 2016).

From Figure 6.1, large numbers of vacant lots and semi-empty parking lots predominate the study area. In many parts of the city, parking lots replaced previously existing buildings that were once hubs for important cultural and social events, but that were left abandoned and in a decrepit state (George et al., 2016). Current plans for revitalization of vacant lots within the study area are underway and include the One World Garden project. The One World Garden is a neighborhood greenspace that celebrates the region's arts and culture as well as Utica's diverse immigrant heritage (R2G, 2010; George et al., 2016).

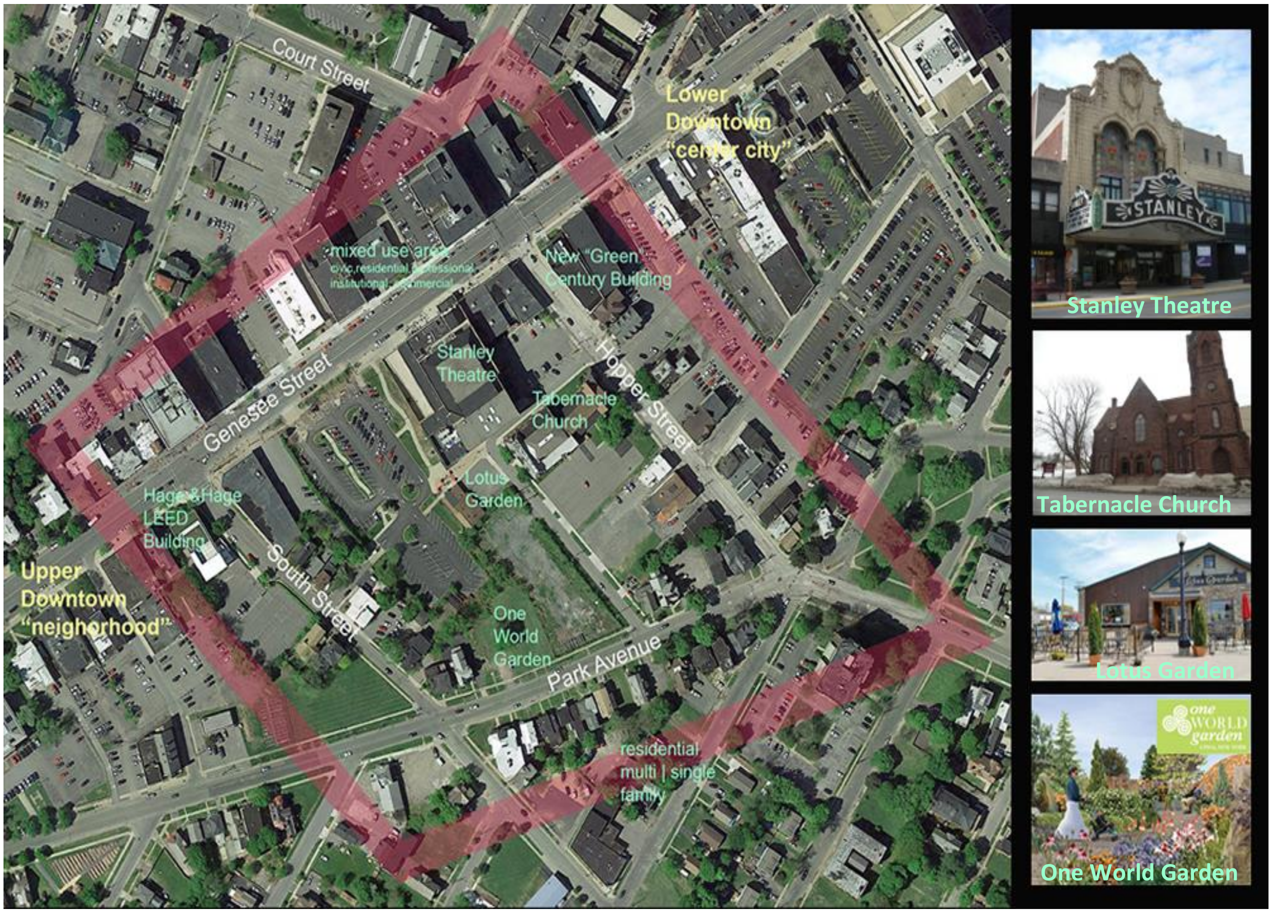

Figure 6.1 - Proposed study area in downtown Utica (in red) that encompasses historical buildings, commercial and residential units, and a number of vacant lots and parking lots.

The study area outlined in Figure 6.1 promises to become an example of revitalization success if sustainable development practices are carefully planned and adopted. Sustainable community development has been linked to higher levels of human happiness. Studies have suggested that happier communities incorporate aspects of environmental, economic, and social sustainability (O'Brien, 2001; O'Brien, 2005; Florida et al., 2013; Leyden et al., 2011; Cloutier et al., 2014). The frameworks and tools presented in this chapter may become part of the strategic planning of city planners and engineers to incorporate sustainable elements that advance the overall social, economic, and environmental wellness of our communities.

Chapter 6: Development of the GeoDistrict Energy Tool for Sustainable Neighborhood Design

As described by Reber et al. (2013), the revitalization of sustainable communities must include a collaborative approach (systems approach) that considers the diverse needs of the community, including local residents and leaders, stakeholders, and university partners. For the study presented in this chapter, one meeting was held in Utica to solicit input from the community for the development of frameworks and tools in sustainable neighborhood design. Some of the comments obtained from the meeting were considered in the study. However, a follow-up meeting with the community did not ensue, and interest in the development of the project soon vanished. For the design of complex systems in the revitalization of sustainable communities, a systems approach that ensures continuous collaboration with local residents, leaders, and university partners is essential for a successful project design and implementation.

LEED-ND Audit

As discussed by Moreno-Long (2016), the Leadership in Energy and Environmental Design for Neighborhood Development (LEED-ND) audit tool was employed in downtown Utica to assess the existing urban and sustainability conditions of the area. The LEED-ND tool is a rating system that measures integrative components of smart growth and green building practices in urban neighborhoods. The tool was developed by the United States Green Building Council (USGBC), the Congress for the New Urbanism (CNU), and the Natural Resources Defense Council (NRDC) (U.S. GBC, 2017).

The LEED-ND audit in downtown Utica focuses on a forty-seven acre area with “high potential for being catalytic in spurring downtown revitalization”. The audit serves as a baseline metric to compare current urban and sustainability conditions against any measureable improvements in the future. In addition, the audit outlines the area’s strengths and weaknesses in adopting smart growth and green building practices, and provides recommendations for moving forward with sustainable design practices (Moreno-Long, 2016).

Moreno-Long (2016) analyzed three LEED-ND categories in downtown Utica: 1. Smart Location and Linkage; 2. Neighborhood Pattern and Design; and 3. Green Infrastructure and Building. The Smart Growth Location and Linkage (SLL) and the Neighborhood Pattern and Design (NPD) categories aim to minimize sprawl by considering the area's location, accessibility to diverse services, neighborhood greenspaces, public transit, and alternative transportation modes.

The SLL category examines new development in areas of existing development, like downtown areas and their surroundings, in order to preserve land and minimize the environmental damages of new development. The NPD category considers mixed-use compact neighborhoods with convenient access to diverse services and public spaces by encouraging various modes of transportation. Walking, biking, use of public transportation, and short driving commutes are highly encouraged activities listed under the NPD category (U.S. GBC, 2017).

The Green Infrastructure and Building (GIB) category addresses the environmental damages of construction, operation, and infrastructure of existing and new neighborhoods. GIB enables choices that favor sustainable building materials and technologies to reduce energy and water waste. Specifically, the use of energy efficiency technologies and renewable energy in buildings, as well as the preservation of local vegetation, can help reduce stormwater runoff and alleviate the urban heat island effect in cities (U.S. GBC, 2017).

From the LEED-ND audit in downtown Utica performed by Moreno-Long (2016), the downtown area received approximately 18%, 29%, and 7% of all possible points for the SLL, NPD, and GIB categories, respectively. The SLL category received only 5 of the 28 possible points due to limited public transportation options and the lack of designated bicycle traffic lanes. A higher number of points for SLL can be achieved if the city develops diverse infrastructure options and provides comprehensive public transportation plans (George et al., 2016; Moreno-Long, 2016).

The NPD category received the highest number of points (12 of 41 points) because of accessibility to public parks, recreation areas, and local food production. However, the prevalence of vacant lots and semi-empty parking lots decreased the number of possible points for NPD. The transformation of vacant lots and parking lots into usable public spaces, areas with green infrastructure, or renewable energy development can help increase the number of points for NPD (George et al., 2016; Moreno-Long, 2016).

Finally, the GIB category received the lowest number of points (2 of 28 points) because few of the area's historic buildings have undergone retrofitting to improve energy and water efficiency (Moreno-Long, 2016). Retrofitting historic buildings or new constructions that incorporate sustainable building materials and energy efficient technologies can help increase the number of points for GIB (George et al., 2016; Moreno-Long, 2016).

Data Collection and Analysis

To assess the energy usage patterns of the study area, energy consumption data was collected and analyzed by the Cornell group for the Stanley Theater, Tabernacle Church, and Lotus Garden Restaurant. From Figure 6.2, the monthly electricity and natural gas consumption for the Stanley Theater for years 2012 - 2015 shows higher consumption during the fall and winter months and lower consumption during the spring and summer months. As expected in

Upstate NY, natural gas consumption is the highest during the months of November through May, with little to no consumption during the summer months (Stanley Theater, 2015).

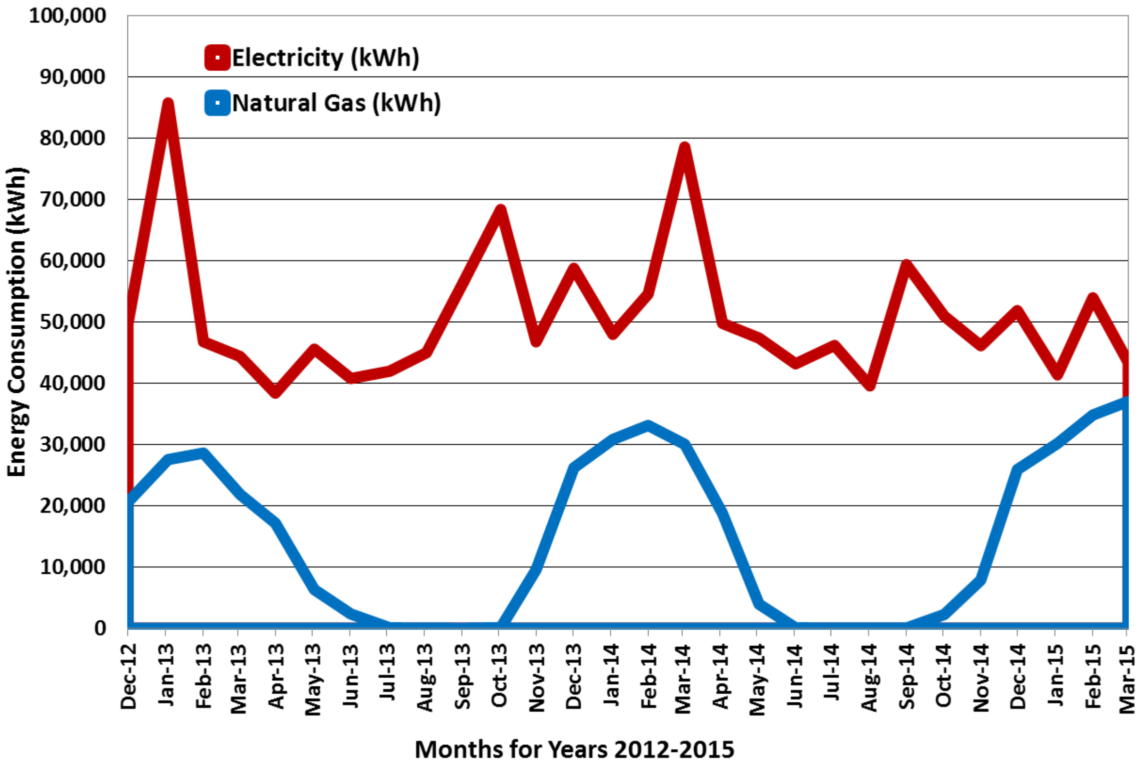

Figure 6.2 - Electricity (red) and natural gas (blue) consumption for the Stanley Theater for years 2012 – 2015 based on utility bills collected and analyzed (Stanley Theater, 2015).

The heating system of the Stanley Theater includes steam boilers converted from oil-fired to natural gas around the late 1970s, and the cooling system consists of evaporative cooling with a few mini-split and central air conditioning systems. The electricity load of the theater exceeds the consumption of natural gas used for heating possibly due to the large electrical demand of stage lighting systems (LPA, 2015). The annual energy demand for the Stanley Theater is estimated to vary year-to-year depending on the type and frequency of scheduled events (Stanley Theater, 2015). The size of the Stanley Theater is estimated around 53,700 $ft.^2$ of gross floor area (City of Utica, 2017).

From Figure 6.3, the monthly electricity and natural gas consumption for the Tabernacle Church for years 2012 - 2014 records the natural gas demand much higher than the electricity demand during the winter months. For space heating, the church uses a forced hot-water system with baseboard radiators. There is no cooling system for the building during the summer months. The electricity load of the church remains relatively constant during the recording period, and is only slightly higher during the summer months of July through September. Although the church is open and active during the weekdays, most of the services take place on Saturday and Sunday. Therefore, the highest energy consumption is expected to occur during the weekends and religious holidays (Tabernacle Baptist Church, 2015). The size of the Tabernacle Baptist Church is estimated around 25,400 ft.^{2} of gross floor area (City of Utica, 2017).

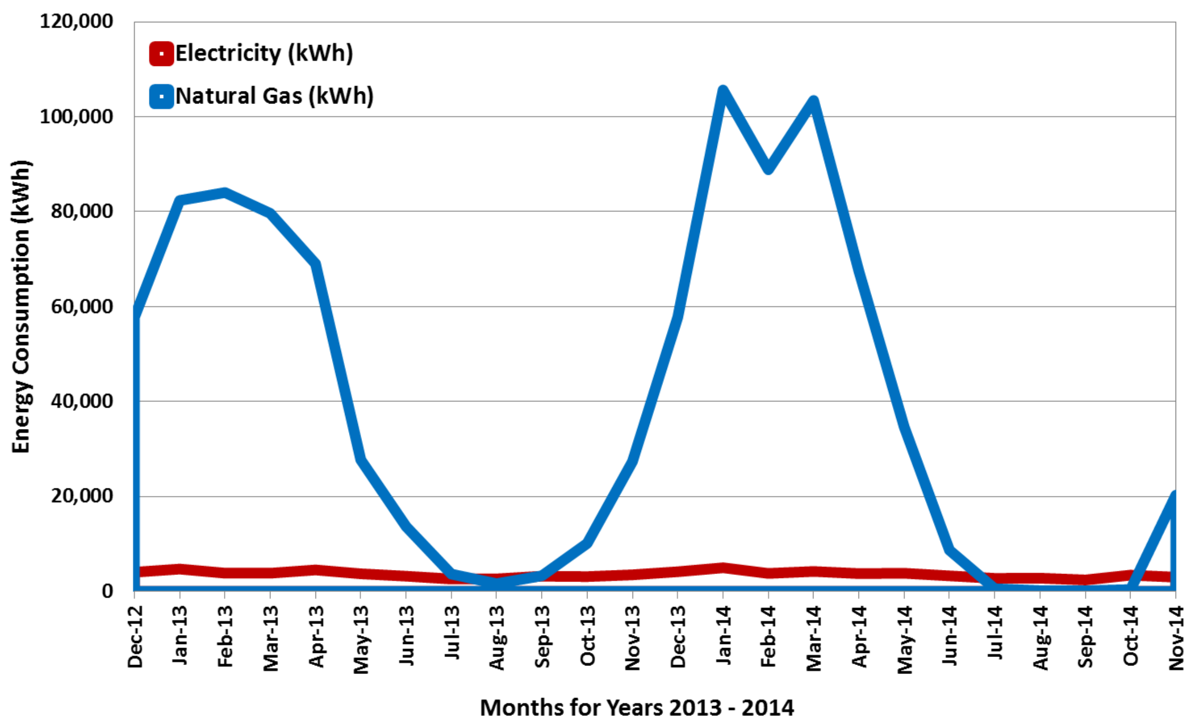

Figure 6.3 - Electricity (red) and natural gas (blue) consumption for the Tabernacle Baptist Church for years 2012 – 2014 based on utility bills collected and analyzed (Tabernacle Baptist Church, 2015).

The electricity and natural gas consumption for the Lotus Garden Restaurant, in Figure 6.4, shows a similar pattern to that of the Tabernacle Church. Natural gas consumption is highly seasonal and exceeds electricity consumption during the winter months. Electricity consumption is only slightly higher than natural gas consumption during the summer months. For space heating and cooling, the restaurant uses a forced-hot water system with baseboard radiators and a central air conditioning system, respectively. The Lotus Garden Restaurant opens daily in the afternoons and evenings, and is expected to have a more continuous year-to-year annual energy demand and usage pattern (Lotus Garden Restaurant, 2015). The size of the Lotus Garden Restaurant is estimated around 3,500 ft.^{2} of gross floor area (City of Utica, 2017).

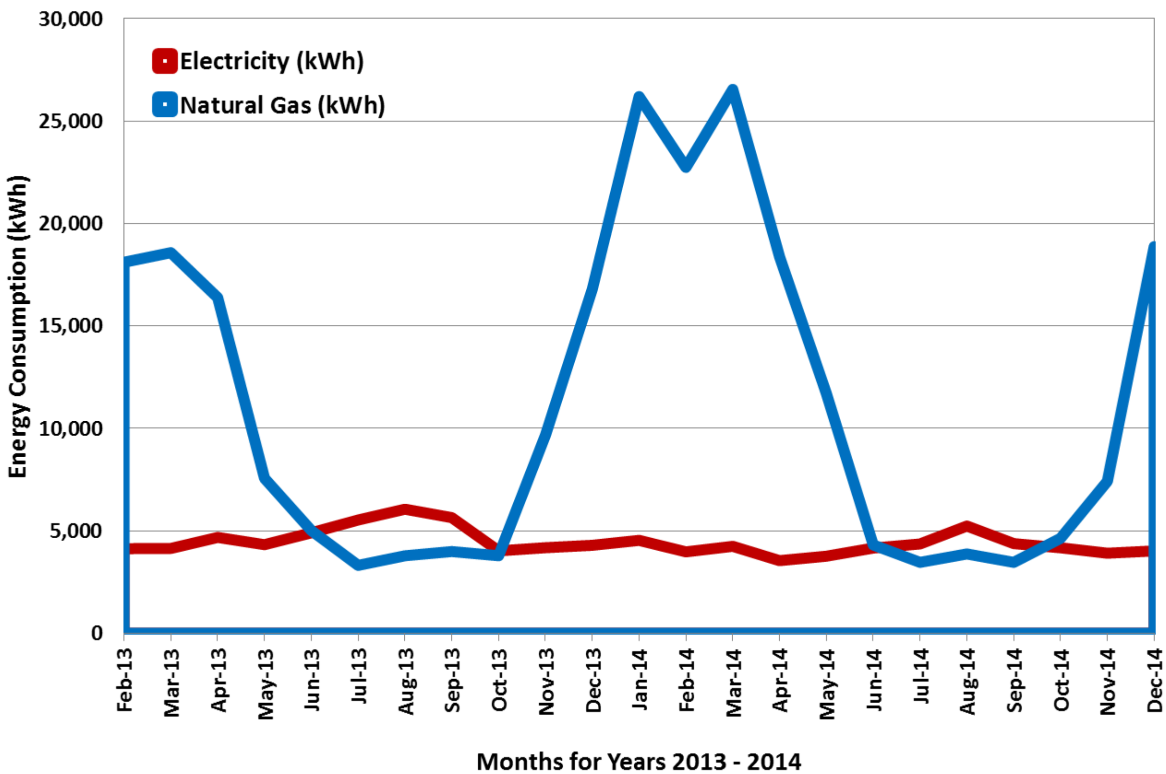

Figure 6.4 - Electricity (red) and natural gas (blue) consumption for the Lotus Garden Restaurant for years 2013 – 2014 based on utility bills collected and analyzed (Lotus Garden Restaurant, 2015).

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Energy consumption data was not collected for residential units within the study area because all of the units sampled were vacant. In order to provide building retrofitting recommendations and adequately design GSDE systems within the study area, heating and cooling load calculations were performed by inspecting building characteristics. Specifically, the inspection of three residential units, Lotus Garden Restaurant, Tabernacle Church, and Stanley Theatre included measuring exterior doors and windows, room partitions, and estimating building materials for doors, walls, and insulation (Prathibha, 2016).

Prathibha (2016) analyzed three residential units representing different occupancies: 1-family; 2-family; and an apartment. The residential units were constructed during different time periods from 1880 through 1950, and varied in size from 1,900 – 3,900 $ft.^2$ of gross floor area (Prathibha, 2016). To assess the thermal properties of building materials, a survey of typical construction materials for different time periods obtained from the U.S. Department of Housing and Urban development was used (U.S. HUD, 1980).

From the data collected and analyzed, Prathibha (2016) calculated surface area and thermal characteristics of doors, windows, and walls to assess the buildings' heat losses and infiltration losses. For residential buildings, the typical peak heating load of the buildings sampled ranged from 100,000 – 125,000 Btu/hr. Similarly, a peak heating load for the Lotus Restaurant, representative of a small commercial building, was estimated around 143,000 Btu/hr. The Tabernacle Church is representative of a mid-size commercial building with an estimated heat load around 1,025,000 Btu/hr. The Stanley Theater is representative of a large commercial building with an estimated heat load around 1,663,000 Btu/hr. For the GSDE examples provided in sections 6.3 and 6.4, typical peak heating load for buildings with varying sizes and loads follow the estimates provided in this section.

Heating and cooling load calculations are often performed as a method to facilitate the design and selection of heating, ventilation, and air conditioning systems (HVAC), including geothermal heat pump (GHP) systems. In Upstate NY, heating loads surpass cooling loads because typical heating and cooling degree days can exceed 6,800 and 500, respectively (NYSERDA, 2017a). When sizing HVAC or GHP systems, the equipment should be sized to handle the greater of the peak heating or cooling load of the area (IGSHPA, 2009).

The peak heating load represents the amount of heat lost from the inside of the building to the outdoor environment at a designed winter indoor and outdoor temperature condition. The peak heating load accounts for heat loss through windows, walls, floors, ceilings, and infiltration (U.S. HUD, 1980; IGSHPA, 2009; Burdick, 2011).

Likewise, the peak cooling load represents the amount of heat gained inside the building from the outdoor environment at a designed summer indoor and outdoor temperature condition. In addition to the heat gains through windows, walls, floors, ceilings, and infiltration, peak cooling loads consider internal gains from occupants, appliances, solar radiation, and lighting (U.S. HUD, 1980; IGSHPA, 2009; Burdick, 2011).

6.2.2: Building Retrofitting

For many Rust Belt cities, retrofitting residential and commercial buildings is necessary due to the structures' age, long periods of vacancy, and lack of maintenance. In Utica, many buildings were constructed in the late 19th to mid-20th century with construction materials that do not adhere to current standards (CCE, 2012; Prathibha, 2016). Poor construction materials and lack of proper maintenance may influence the energy performance of such buildings resulting in energy that is wasted due to these inefficiencies.

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Due to Utica's strong historical preservation efforts, many of the city's buildings are listed under the National Registry of Historic Places, and cannot be completely demolished or reconstructed, leaving retrofitting as the only option. Several historical buildings in downtown Utica, including the Stanley Theater and Tabernacle Church, have recently undergone renovations and have abundant opportunities for growth (Stanley Theater, 2015; Tabernacle Baptist Church, 2015). Other promising examples around the area include the Hage & Hage LLC building retrofitting that is expected to save more than $16,000 in annual energy costs (Hage & Hage LLC, 2015).

In 2012, a study led by the Cornell Cooperative Extension in Oneida County suggested that most houses in the county lack proper insulation, have cracks and holes in ceilings and walls, and have outdated lighting, appliances, and HVAC systems (CCE, 2012). The study estimates that a typical home in Oneida County would require between $8,000 to $13,000 of renovations and retrofitting to reduce residential energy use by 35% (CCE, 2012). Proper sealing and insulation of buildings can result in total energy savings of 10 - 15%, and up to 20% of savings in heating and cooling costs (George et al., 2012).

From the energy data collection and analysis of commercial and residential buildings presented in Section 6.2.1, Prathibha (2016) developed a list of retrofitting measures that could contribute to reductions in energy use. Prathibha (2016) modeled several units within the study area using Transient System Simulation Program (TRNSYS) to assess the estimated capital cost per retrofit, energy savings, and simple payback period.

Prathibha (2016) estimated that the costs and payback period for adding insulation, installing double-paned windows, caulking doors, reinforcing walls, roof relayering, and upgrading of lighting and energy-intensive appliances could amount to over $60,000 with a payback period of 11 years for an individual residence. In addition, applying the recommended retrofits to each of the residences sampled could result in annual energy savings of over 17 MMBtu (>5,000 kWh_e) and 347 MMBtu (>100,000 kWh_{th}) for electricity and natural gas consumption, respectively (Prathibha, 2016).

Building retrofitting is an urgent need within the study area, especially in the residential units sampled. Prior to considering renewable energy integration within a community, energy conservation measures through building retrofits must become a priority. Although building retrofitting incurs a significant upfront cost, the benefits are translated into energy savings that extend well after the estimated payback period of 11 years, and an improved quality of life for the residents.

Financial incentives in the form of rebates, grants, and tax deductions are available for commercial and residential building retrofitting but vary year-to-year. On the federal level, a personal tax credit of 10% is available for improving the energy efficiency of residential building envelopes, including upgrading insulation, windows, and doors. For commercial buildings, a federal tax deduction of up to $1.80 per square foot is available for retrofits that include energy-efficient lighting, heating, cooling and ventilation system, and reductions to the building's envelope (Prathibha, 2016; DSIRE, 2017).

6.2.3: Solar Energy

Over the past few years, solar energy development in NY has significantly increased due to Governor Cuomo's $1 billion dollar initiative to promote solar energy as part of the "Cleaner, Greener Communities Program" (Mohawk Valley, 2011). It is estimated that from 2011 to 2014, solar development in the state increased by 300%, which is twice the rate of solar growth nationwide (DEC, 2017).

Examples of solar energy applications in Oneida County include the installation of solar photovoltaic (PV) panels on various residential units, and in a parking garage and City Hall in Rome, NY (Campbell, 2014). In Utica, Mohawk Valley Community College (MVCC) committed to a 2.8 MW solar project that could provide for 35% of the college's total electricity load and save $90,000 in the first year of operation (MVCC, 2015).

Using the data collected for energy consumption for the buildings sampled within the study area (Section 6.2.1), Sud (2016) assessed the feasibility of providing the study area's electricity usage from solar PV installations. Sud (2016) analyzed the technical and financial feasibility of installing solar PVs in commercial and residential buildings and in solar farms on nearby vacant lots. Sud (2016) estimated solar PV system capacity, capital costs, and payback periods for each installation option.

For commercial buildings, Sud (2016) considered solar PV roof installations for the Stanley Theater, Tabernacle Church, Lotus Garden Restaurant, and Firestone Auto Care. The large available flat roof area of the theater and the auto care building suggests that an installation of a 163 kW system is possible on each building, with an installation cost over $160,000 and payback period of around 9 years. The percent of energy recovered from solar PVs could amount to over 25% of the Stanley's electricity consumption. No sample energy data were collected for the auto care building; therefore, the percent of energy covered from solar PV's is currently unknown for Firestone Auto Care (Sud, 2016).

For the Tabernacle Church, the building's roof orientation and 20° slope suggests that a 37 kW system providing for over 75% of the building's energy consumption is possible with a cost of around $40,000 and payback period of 13 years. The roof orientation, slope, and size of the Lotus Garden Restaurant resulted in the least economical option among the commercial buildings sampled. For the restaurant, an installation of a 30 kW system providing for over 45% of the building's energy consumption is possible with a cost of around $35,000 and payback period of 17 years (Sud, 2016).

For residential buildings within the study area, Sud (2016) determined that units with south facing roofs would be ideal for solar PV installations due to Utica's latitude of 43°N. The system capacity for a representative residential unit within the study area could be 6 kW with a cost of around $6,000 and payback period of 11 years (Sud, 2016).

Sud (2016) analyzed the possibility of using two local government-owned vacant areas for solar PV farm installations located about 0.5 miles from the study area. Collectively, the vacant lots could provide for all of the area's electricity demand even if only 50% of the 76,000 square feet lot area is used for solar PV installations. Sud (2016) estimated that in order to cover 100% of the area's current electricity demand, an installation of a 4.6 MW system would be necessary with a cost of around $3.9 million dollars and payback period of 8 years.

As presented by Sud (2016), there are several solar PV system installation options for the study area. From the analysis, the option that supplies all of the area's electricity demand and results in the lowest payback period is the installation of solar PV farms. Using nearby vacant lots for solar PV farm installations also presents the possibility of future expansion to surrounding neighborhoods. To achieve such an installation, local government officials, utility companies, and neighborhoods would have to work in collaboration, much like community solar programs work today (NYSERDA, 2015).

Solar PV development in Utica presents a financial opportunity for growth and revitalization of the local economy, as well as an environmental opportunity to transition to renewable energy sources. Currently, solar PV installations benefit from a number of local, state, and financial incentives in the form of rebates, grants, loans, and tax credits for both commercial and residential applications.

On the federal level, a 30% tax credit is available for both residential and commercial solar PV installations. On the state level, the NY Sun Incentive Program provides various cash incentives for residential and commercial solar PV installations based on system capacity. Incentives for solar PV installations vary year-to-year; however, federal tax incentives are expected to decrease over the next few years as a result of decreases in solar PV installation costs and increases in market penetration rates (DSIRE, 2017).

6.2.4: Geothermal (Ground-Source) District Energy

Space heating and cooling in residential and commercial buildings can account for 40 – 60% of a building's energy consumption (Mahlmann and Escobedo, 2012). In NY, nearly 32% of the state's energy-related greenhouse gas emissions (GHG) result from the consumption of fossil-fuel energy, primarily natural gas, propane, and oil, for space heating, cooling and domestic hot water needs in residential and commercial buildings. Recently, Governor Cuomo announced a $15 million dollar proposal to increase the use of renewable heating and cooling technologies in NY with the goal to achieve a 40% reduction of GHG emissions by 2030 relative to 1990 levels (NYSERDA, 2017b).

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Despite the lack of high-grade geothermal energy resources in NY for electricity generation or direct-use applications, development has been possible with the use of shallow geothermal or ground-source heat pump (GHP) systems. GHPs utilize the thermal energy stored in the ground at relatively shallow depths (≤500 feet) to efficiently provide for space heating and cooling, and domestic hot water needs (GHPC, 2004; Beckers, 2016; George et al., 2016).

In Utica, several commercial and apartment buildings have undergone energy efficiency improvements that include GHP installations. In 2007, the Hage & Hage LLC building installed a GHP system with 25 wells, each at depths of 420 feet, for space heating and cooling. The retrofitted building also includes high-efficiency lighting and improved building envelope insulation. Hage & Hage LLC estimate that the annual energy and cost savings from building retrofitting are over 60,000 kWh and nearly $17,000, respectively (Albany Law School, 2007; Hage & Hage LLC, 2015).

Other GHP installations in Utica include the renovation of two residential buildings to support the Johnson Park Apartments V, which provide housing to families in need. In 2012, Apartment V opened as LEED Platinum certified with three geothermal wells, each ranging in depths from 250 – 290 feet, in each of the two residential building (JPC, 2012).

The feasibility of installing GSDE systems within the study area in downtown Utica is explored in sections 6.3 and 6.4. Specifically, an integrative framework and tool called "GeoDistrict Energy" is developed in Section 6.3 to assess the technical and economic feasibility of installing GSDE systems at a neighborhood-scale. In Section 6.4, several case studies are proposed for GSDE installation in parking lots and vacant lots within the study area. In addition, Section 6.4 compares the technical and economic analyses for each of the case studies considered.

6.3: Introduction to the GeoDistrict Energy Tool

Planning for renewable energy projects involve several phases that include feasibility assessments, site appraisal, project design, construction, and operation of the system, among others (Àrmannsson et al., 2010). For many city planners and engineers, budgeting for renewable energy projects is challenging due to high uncertainties and risks of project success, intense capital expenditure required, and the current low energy prices for fossil fuels.

To facilitate geothermal project development prior to construction, several tools and software exist that design, model, and simulate various system configurations and assess their techno-economic performance. For the design of GHPs, programs such as GCHPCalc, GLHEPro, and Geo-Connections, among others, provide analyses of system configuration options, size, and performance for long periods of time (>20 years). Many of the programs available for GHPs design require the user's knowledge and expertise in the subject, and often involve purchasing of the software (GeoKISS, 2012; IGSHPA, 2015; Geo-Connections, 2017).

The GeoDistrict Energy tool created for this project and presented as part of this dissertation was developed to provide a first-order approximation of the technical and economic feasibility of installing GSDE systems in small to mid-size communities for heating and cooling applications. The tool applies design and installation principles of GHP and district energy networks, and adapts to various geographic and geologic regions by modifying the assumptions embedded in the model (IGSHPA, 2009; Jóhannesson, 2016).

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The GeoDistrict tool uses a Microsoft Excel interface and is intended for users with minimal to no experience in GSDE system design. The user is expected to follow the design guidelines provided in this section, and to have basic knowledge of technical and economic terminology for assessment of renewable energy projects. In Section 6.3.1, an overview of the GeoDistrict model architecture and content is provided, and model variables, assumptions, primary equations, and output are described. In addition, examples of model implementation for a small area are provided throughout the descriptions in Section 6.3.1.

6.3.1: GeoDistrict Energy Tool Content Description

The GeoDistrict tool developed in Microsoft Excel contains six tabs: 1. Model Description; 2. Heat Load & Distribution; 3. Geothermal Model; 4. GeoDistrict Energy Model; 5. Summary Graphs; 6. Unit Conversions.

Tab 1. Model Description

The Model Description tab provides general information on model content, legend, and usage instructions. The tabs containing Heat Load & Distribution, Geothermal Model, and GeoDistrict Energy Model are divided into four sections: A. Designer Input; B. Model Variables; C. Model Assumption; D. Model Output. The Designer Input section is distinguished by blue color and represents the primary input section of the model. In the Designer Input section, the user should specify information pertaining to the expected heat load of the buildings to be covered by the GSDE system, size of the geothermal field(s) installation based on available open lots, and distances from the heat central to the connected buildings.

The Model Variables section, in gray color, includes GSDE design and installation principles from manuals and literature review. In this section, the primary model equations are provided, which require knowledge and understanding of GSDE design and installation practices. The user should not modify the Model Variables section.

The Model Assumptions section, in pink color, allows the user to make changes on equipment selection, economic assumptions, geologic properties, and climatic characteristics, among other relevant assumptions. Case studies for a particular geographic or geologic region can be made by modifying the Model Assumptions section in both tabs 3. Geothermal Model and 4. GeoDistrict Energy Model.

The Model Output section, in yellow color, represents the technical and economic results of implementing the GeoDistrict tool based on input data, model variables, and assumptions. The Model Output section should not be modified. Table 6.1 summarizes the four sections (A. Designer Input; B. Model Variables; C. Model Assumptions; and D. Model Output) embedded in the Heat Load & Distribution, Geothermal Model, and GeoDistrict Energy Model tabs.

Table 6.1 - Summary instructions for the four sections included in the Heat Load & Distribution, Geothermal Model, and GeoDistrict Energy Model.

Geothermal District Energy Model - Legend Description	
A. Designer Input	**GO:** User **SHOULD** input building description, design heat load per unit, geothermal field size, and distance from heat central.
B. Model Variables	**STOP:** User **SHOULD NOT** modify the models for mechanical equipment, geothermal installation, economic, climatic, energy production, energy distribution, and energy consumption. Equations obtained from the authors listed in the references section.
C. Model Assumptions	**GO:** User **CAN** modify assumptions on mechanical equipment selection, economic assumptions, geologic properties, and climatic characteristics, among others. Understanding of mechanical equipment submittal data and ground characteristics are required.
D. Model Ouput	**STOP:** User **SHOULD NOT** modify this section as it directly relates to the designer input, model variables, and model assumptions.

Tab 2. Heat Load & Distribution

The Heat Load & Distribution tab allows the user to describe characteristics of estimated building heat loads and distribution distances from the heat central location to the consumer buildings. The heat central location is adjacent to the geothermal field(s) and houses heat pumps and auxiliary boilers connected to the supply and return distribution pipelines.

In Table 6.2, a detailed description and user instructions for the Heat Load & Distribution Designer Input and Model Variables sections is provided. The Designer Input section in Tab 2A includes a list of nodes, description of building types per node, number of units per node, heat load per unit, distance of each node from the heat central location, and total estimated pipeline distribution length for all nodes. The Model Variables section in Tab 2B include the total node heat load and total estimated heat load for all nodes computed from the user's input data.

In the Designer Input section, the Nodes column can represent a single building with a unique heat load and distance from heat central, or multiple buildings with similar heat load characteristics and distances from heat central. The model is designed for up to 21 nodes comprised of either single or multiple buildings. If additional nodes are required, rows reflecting the modifications can be added in the model with the corresponding design equations in the gray areas.

The Description column allows for qualitative information on the type of building(s) considered within each node. The No. of Units column represents the number of buildings considered within each node. If more than one building is considered within a node, the units should share similar heat load characteristics and travel distances from the heat central location.

The Heat Load per Unit column represents the required peak heating or cooling load per building to be supplied by the GSDE system. A building heating and cooling load analysis should be performed prior to the GeoDistrict tool implementation. In geographic regions with high heating demand, the building peak heating load is considered for sizing GHP systems. Likewise, in regions with high cooling demand, the building peak cooling load is considered.

The Distance from Heat Central column represents the distribution distance from the heat central location to a specific node via a network of insulated supply and return distribution pipelines. The Total Estimated Pipeline Distribution Length for all Nodes considers the total piping length for the entire distribution network.

The Total Node Heat Load column, in gray color, is computed by multiplying the Heat Load per Unit column by the No. of Units column. The Total Estimated Heat Load for all Nodes summarizes the heat load per node, and should not be modified as it becomes an input to the Geothermal Model (Tab 3) and GeoDistrict Energy Model (Tab 4) in order to adequately size the geothermal fields and distribution pipelines.

Table 6.2 - Heat Load & Distribution Model section description and user instructions.

Tab 2. Heat Load & Distribution	Section Description and User Instructions
A. Designer Input	**Nodes:** single building with unique heat load and distance from heat central, or multiple buildings with similar heat load characteristics and distances from heat central . **User SHOULD populate field.**
	Description: type of building(s) or units considered within each node. Could be either a cluster of residential homes or commercial buildings. **User SHOULD populate field.**
	No. of Units: number of building(s) considered within each node. If more than one building considered within a node, units should have similar characteristics for heat load and distribution distances from heat central location. **User SHOULD populate field.**
	Heat Load Per Unit: required peak heatingor cooling load per building to be supplied by the geothermal district energy system. A building heating and cooling load analysis should be performed prior to the GeoDistrict Energy tool implementation. **User SHOULD populate field.**
	Distance from Heat Central: distribution distance from the heat central location to a specific node via a network of insulated pipes. **User SHOULD populate field.**
	Total Estimated Pipeline Distribution Length for all Nodes: total pipeline length for entire distribution network. **User SHOULD populate field.**
B. Model Variables	**Total Node Heat Load:** total node design heat load requirement to be covered by the geothermal system. The Total Node Heat Load is the No. of Units x Heat Load Per Unit. **User SHOULD NOT populate field.**
	Total No. of Units for all Nodes: sum of the number of units based on designer input data. **User SHOULD NOT populate field.**
	Total Estimated Heat Load for all Nodes: sum of the total node heat load for all nodes. **User SHOULD NOT populate field.**

In Table 6.3, an example of the Heat Load & Distribution model applied to four nodes representative of the mixed-use residential and commercial buildings sampled in Section 6.2.1 is provided. Three commercial buildings, with varying sizes and heat loads, and 10 residential buildings with similar loads result in a total estimated heat load and pipeline distribution length for all nodes of over 3.8 MMBtu/hr and over 1,000 feet, respectively. Specific case studies for the study area in downtown Utica are provided in sections 6.4 – 6.4.4.

Table 6.3 - Heat Load & Distribution Model applied to four nodes with varying building sizes and load characteristics. The areas in blue color should be populated with information relevant to the study area. The areas in gray should not be populated nor modified.

Nodes	Description	No. of Units	Heat Load (Btu/hr) per unit	Total Node Heat Load (Btu/hr)	Distance from Heat Central (ft)
Node 1	Commercial (Large)	1	1,663,000	1,663,000	188
Node 2	Commercial (Mid)	1	1,025,000	1,025,000	134
Node 3	Commercial (Small)	1	143,000	143,000	187
Node 4	Residential	10	100,000	1,000,000	944

Total No. Units for all Nodes:	**13**
Total Estimated Heat Load (Q_L) for all Nodes (Btu/hr):	**3,831,000**
Total Estimated Pipeline Distribution Length (L_{DP}) for all Nodes (ft):	**1,248**

Tab 3. Geothermal Model

The Geothermal Model tab applies technical and economic principles to offer a first-order approximation of the energy and costs of providing space heating and cooling to a community with GHP systems. The model considers vertical closed-loop GHP installations in vacant areas or parking lots surrounding the study area. In many Rust Belt cities, vacant areas, parking lots, and decaying infrastructure are prevalent in major parts of the city, and present opportunities for revitalization with sustainable practices.

In Table 6.4, a detailed description and user instructions for the Geothermal Model Designer Input, Model Variables, Model Assumptions, and Model Output sections is provided. The Designer Input section in Tab 3A considers the geothermal field size, specifically the length and width of the expected installation area, and the design borehole length of each individual vertical well. In gray color, the Total Estimated Heat Load for all Nodes is an input from Tab 2B (Heat Load & Distribution) and should not be modified. The user should only populate the Geothermal Field Characteristics sections listed in blue color.

The Model Variables section in Tab 3B includes principal design equations for the Geothermal Loop Installation Design, Mechanical Equipment Selection, and Economic and Climatic models. This section generates results based on the Designer Input data from tabs 2 and 3. The Geothermal Loop Installation Design includes the number of boreholes and total borehole design length for each field, expected mass flow rates, and total heating capacity of the geothermal field(s) at design capacity. The Mechanical Equipment Selection includes estimated number of heat pump units and heat pump heating/cooling capacity at design conditions.

The Economic Model Variables calculates the annual heating and cooling energy consumption, using costs provided for case studies that include business-as-usual (BAU) and GHP installations. In addition, costs for the mechanical equipment and geothermal loop installation are included in this section. The Climatic Model Variables provide typical yearly heating and cooling load calculations based on degree days, a dataset imported from Tab 3C. The Model Variables for the Geothermal Model section should not be populated, and should only be modified if the user elects to change the principal design equations.

The Model Assumptions section in Tab 3C includes data collected from various sources on mechanical equipment selection, geothermal loop design, and economic and climatic characteristics for the study area. Mechanical Equipment Selection data were collected from available submittal sheets, and include heat pump performance data for a range of heating and cooling operations. The Geothermal Loop Installation Design includes information on minimum required borehole-to-borehole spacing, estimated ground temperatures and thermal conductivity, and diameter of bore and U-bend pipe, among other design assumptions.

In the Economic Model Assumptions, estimates for the cost of geothermal loop installation, purchases of mechanical equipment, pumps and piping, and installation and annual maintenance costs for heat pumps are provided. In addition, estimates on energy prices, inflation and discount rates are included. The Climatic Model Assumptions include outdoor heating and cooling design temperatures, and typical heating and cooling degree days. The Model Assumptions section for the Geothermal Model should be modified if different mechanical equipment is selected, and if an analysis of a particular geologic and geographic location other than Utica, NY is intended.

The Model Output section in Tab 3D summarizes the Designer Input data, Model Variables and Assumptions previously described. This section reports the heating ratio at design conditions for each geothermal field(s), estimated capital costs (CAP), lifetime operation and maintenance costs (LOM), and total cost of ownership (TCO) for the geothermal field(s) and heat pump installation. The Model Output for the Geothermal Model section should not be populated, and should only be modified if the user elects to change the financial metrics of the model.

Table 6.4 - Geothermal Model section description and user instructions.

Tab 3. Geothermal Model	Section Description and User Instructions
A. Designer Input	**Total Estimated Heat Load for all Nodes:** design heat load for all nodes from Tab 2. Heat Load & Distribution. **User SHOULD NOT populate this field**, but SHOULD populate the Heat Load Per Unit input in Tab 2.
	Geothermal Field Characteristics: dimensions of the expected geothermal field size (length and width), and single borehole design length of the geothermal loop assuming vertical installations. **User SHOULD populate fields. User SHOULD NOT populate Area of Installation Site.**
B. Model Variables	**Geothermal Loop Installation Design:** number of boreholes based on field length and width, mass flow rates, total borehole design length for each geothermal field, and total heating capacity of the geothermal field at design conditions. Fields relate to design equations and assumptions listed in the chapter. **User SHOULD NOT populate fields.**
	Mechanical Equipment Selection: number of heat pump units at design conditions, heat pump tonnage per unit, and total heat pump heating capacity at design conditions. Fields relate to equations and assumptions listed in the chapter. **User SHOULD NOT populate fields.**
	Economic Model: annual heating/cooling energy consumption and costs for business-as-usual, heat pump mechanical equipment and installation costs, loop installation costs, annual electric costs of heat pumps in heating/cooling mode. Fields relate to design equations and assumptions listed in the chapter. **User SHOULD NOT populate fields.**
	Climatic Model: yearly heating/cooling load, heating/cooling load per degree day, fraction of the year in heating/cooling load. Fields relate to design equations and assumptions listed in the chapter. **User SHOULD NOT populate fields.**
C. Model Assumptions	**Mechanical Equipment Selection:** heat pump model and performance characteristics from submittal data sheets for a range of heating/cooling operations. **User CAN modify fields based on heat pump submittal data and location characteristics.**
	Geothermal Loop Installation Design: minimum borehole-to-borehole spacing, ground temperature, thermal conducitivity of ground and grout, diameter of bore and U-Bend pipe, loop installation cost. **User CAN modify fields based on location and geologic characteristics.**
	Economic Model: geothermal loop installation cost, mechanical equipment cost, pumps, piping & installation costs, annual maintenance cost for heat pumps, expected lifetime of heat pumps, inflation and discount rates, electricity rates, natural gas rates, incentives. **User CAN modify fields based on location characteristics.**
	Climatic Model: outdoor heating/cooling design temperatures, typical heating/cooling degree days. **User CAN modify fields based on location characteristics.**
D. Model Output	**Geothermal Heat Pump Model:** heating ratio at design conditions, capital costs, lifetime operation and maintenance costs, total cost of ownership. **User SHOULD NOT populate fields.**

In Table 6.5, an example of the Tab 3A Designer Input section applied to one geothermal field (LOT A) is provided. The Designer Input section, in blue color, includes the length and width of the installation site and the borehole design length for a single well. For GHP systems, typical borehole design lengths for a single well can be in the range of 150 – 450 feet deep and should not exceed a depth of 500 feet (GHPC, 2004; Beckers 2016). Drilling permits are required for depths greater than 500 feet. Furthermore, drilling to depths that exceed 500 feet can increase the risks of drilling and well completion, and may influence the GHP performance due to the effect of the geothermal gradient (Beckers, 2016).

Table 6.5 - Geothermal Model Designer Input section applied to one geothermal field (LOT A). The input information in blue color should be populated. The input information in gray color should not be populated nor modified.

GEOTHERMAL MODEL	
A. Designer Input	
Parameter	**Input Information**
Total Estimated Heat Load (Q_L) for all Nodes - (Btu/hr)	3,831,000
GEOTHERMAL FIELD CHARACTERISTICS	
A. Designer Input	
Parameter	**Input Information**
Length of Installation Site LOT A - (feet)	120
Width of Installation Site LOT A - (feet)	105
Area of Installation Site LOT A - (sq. feet)	12,600
Single Borehole Design Length for Field LOT A - (feet)	450

The Total Estimated Heat Load for all Nodes, in gray color, is an input from Tab 2B. The Area of Installation Site per Lot is calculated based on the length and width designer input data. From Table 6.5, the designer input data results in a potential installation area of over 12,000 square feet. The installation size and single borehole length information for up to five lots can be specified in the model. For additional lots, rows reflecting the modifications can be added in the Designer Input, Model Variables, and Model Output sections with the corresponding design equations.

In Table 6.6, an example of the Tab 3B Model Variables section for the design of the geothermal loop applied to one field is provided. The section includes estimates on the geothermal field total number of boreholes (bores), mass flow rates, total borehole design length, and total heating capacity of the field at design conditions.

Table 6.6 - Geothermal Loop Installation Design applied to one geothermal field (LOT A). The Model Variables section, in gray color, relates to design equations and assumptions listed in the chapter and should not be modified.

GEOTHERMAL LOOP INSTALLATION DESIGN	
B. Model Variables	
Parameter	**Variables Information**
Length (feet)/Minimum Bore-to-Bore Spacing LOT A - (feet)	8
Width (feet)/Minimum Bore-to-Bore Spacing LOT A - (feet)	7
Total Number of Bores LOT A - (bores)	56
Mass Flow Rate per Borehole LOT A - (kg/s)	0.8
Total Mass Flow Rate ($\dot{m}$) LOT A - (kg/s)	42
Total Borehole Design Length ($L_{H,T}$) for Field LOT A - (feet)	25,200
Estimated Heating Capacity of the Field at Design Conditions (HC_D) LOT A - (Btu/hr)	1,539,680

The Total Number of Bores per geothermal field is determined from the designer input length and width specification (Tab 3A) divided by the minimum bore-to-bore spacing assumption (Tab 3C). The minimum bore-to-bore spacing can range from 15 – 20 feet (GHPC, 2004; IGSHPA, 2009).

In the model, a spacing of 15 feet from bore-to-bore is assumed. Increasing the spacing can help prevent bore-to-bore thermal interferences (GHPC, 2004; IGSHPA, 2009). The Total Borehole Design Length per geothermal field is determined by multiplying the Total Number of Bores per field times the borehole design length per well. From Table 6.6, over 50 boreholes can be installed in the geothermal field with a total borehole design length of over 25,000 feet.

The total mass flow rate per geothermal field is given by:

$$\dot{m} = \dot{V_{HP}} \bullet \rho_{fluid} \bullet \textit{No. Heat Pumps} \tag{6.1}$$

with $\dot{m}$ = total mass flow rate per geothermal field (kg/s), $\dot{V_{HP}}$ = volumetric flow rate of each heat pump unit (GPM), ρ_{fluid} = density of heat exchanger fluid (kg/m³), and *No. Heat Pumps* = total number of heat pump units installed. The Mass Flow Rate per Borehole is the total mass flow rate per geothermal field divided by the total number of bores per field.

The total heating capacity of the geothermal field at design conditions is given by:

$$HC_D = \frac{L_{H,T} \bullet [T_G - \left(\frac{EWT_{S,H} + LWT_{S,H}}{2}\right)]}{\left(\frac{COP_D - 1}{COP_D}\right) \bullet (R_B + R_G \bullet F_H)} \tag{6.2}$$

with HC_D = estimated heating capacity of the geothermal field at design conditions (Btu/hr), $L_{H,T}$ = total borehole heating design length per geothermal field (feet), T_G = average temperature of the ground (°F), $EWT_{S,H}$ = source entering water temperature at design conditions in heating mode (°F), $LWT_{S,H}$ = source leaving water temperature at design conditions in heating mode (°F), COP_D = dimensionless coefficient of performance at design heating conditions (-), and R_B + $R_G \bullet F_H$ = vertical borehole ground loop resistance in heating mode (hr·ft·°F/Btu) (IGSHPA, 2009).

Values for $EWT_{S,H}$, $LWT_{S,H}$, and COP_D, are listed in the Tab 3C Mechanical Equipment Selection Model Assumptions section (see Table 6.10), and are obtained from heat pump equipment submittal sheets. The expected value for T_G is listed in the Tab 3C Geothermal Loop Installation Design Model Assumptions section (see Table 6.11). The ground loop resistance is calculated from Table B.1 in Appendix B based on parameters listed in the Tab 3C Geothermal

Loop Installation Design Model Assumptions section (IGSHPA, 2009). From Table 6.6, the total heating capacity of geothermal Lot A is estimated to be over 1.5 MMBtu/hr.

In Table 6.7, an example of the Tab 3B Mechanical Equipment Selection section applied to one geothermal field is provided. The section includes the total heat pump heating capacity at design conditions, heat pump tonnage per unit, and estimated number of heat pump units at design conditions.

Table 6.7 - Mechanical Equipment Selection applied to one geothermal field (LOT A). The Model Variables section, in gray color, relates to design equations and assumptions listed in the chapter and should not be modified.

MECHANICAL EQUIPMENT SELECTION - Water-to-Water Geothermal Heat Pump Selection	
B. Model Variables	
Parameter	**Variables Information**
Total Heat Pump Heating Capacity (HC_{HP}) at Design Conditions LOT A - (Btu/hr)	2,008,200
Heat Pump Tonnage per Unit LOT A - (Tons)	70
Estimated Number of Heat Pump Units at Design Conditions LOT A	3

The Total Heat Pump Heating Capacity is the heating capacity of one heat pump unit in heating mode times the estimated number of heat pump units for the entire geothermal field. The heating capacity of one heat pump is listed in Tab 3C (Model Assumptions), and is obtained from submittal sheets based on equipment performance conditions. The Number of Heat Pump Units at design condition is obtained by dividing the estimated heating capacity of the geothermal field by the heating capacity of one heat pump unit in heating mode.

The heating capacity of one heat pump in heating mode and the heat pump unit installed capacity (tonnage) are listed in Tab 3C, and are obtained from the heat pump unit submittal sheets. From Table 6.7, three heat pump units each with an installed capacity of 70 tons will be required for the study area with a heating capacity of over 2 MMBtu/hr, which is about 50% of the total estimated peak heating load for all nodes in this example. Geothermal district heating systems can be designed to cover 50 – 70% of the annual peak load, while still providing for 80 – 90% of the annual heating energy requirements of the area (IDHA, 1983; Emeish, 1999). It is estimated that annual peak heating demand occurs only about 3 – 5% of the time per year. Therefore, the remaining peak heating load not covered by geothermal resources can be covered through supplemental peaking equipment using biomass fuels or fossil fuels (Bloomquist, 2003).

In Table 6.8, an example of the Tab 3B Economic Model section is applied to the BAU scenario and to one geothermal field. The BAU scenario considers providing space cooling and heating with air source heat pumps (ASHP) and with natural gas furnaces (boilers), respectively. The section provides estimates of total annual heating and cooling costs, and estimates of energy rates for mechanical equipment that include ASHPs, furnaces, and water-source geothermal heat pumps (WSGHP), as defined in equations 6.3 – 6.5.

The cooling cost rate for ASHPs is given by:

$$C_{C,ASHP}\left(\frac{\$}{MMBtu}\right) = \frac{10^6\ Btu}{10^3 \frac{W}{kW} \bullet SEER\left(\frac{Btu}{Wh}\right)} \bullet Electric\ Energy\ Cost\left(\frac{\$}{kWh}\right) \tag{6.3}$$

with $C_{C,ASHP}$ = cooling cost rate for ASHPs (\$/MMBtu) and *SEER* = seasonal energy efficiency ratio. *SEER* measures the cooling efficiency of ASHPs. A minimum *SEER* value of 12 is required by the Department of Energy (IGSHPA, 2009).

The natural gas heating rate for furnaces or boilers is given by:

$$C_{H,fur}\left(\frac{\$}{MMBtu}\right) = \frac{10^6\ Btu}{100{,}000 \frac{Btu}{Therm} \bullet AFUE} \bullet Natural\ Gas\ Cost\left(\frac{\$}{Therm}\right) \tag{6.4}$$

with $C_{H,fur}$ = heating cost for furnaces or boilers (\$/MMBtu) and *AFUE* = annual fuel use efficiency. *AFUE* measures average heating efficiencies for certain fuel burning equipment throughout the entire heating season. *AFUE* values for old, inefficient equipment can be as low as 65% and for highly efficient equipment as high as 95% (IGSHPA, 2009).

The cooling cost rate for WSGHPs is given by:

$$C_{C,WSGHP}\ \left(\frac{\$}{MMBtu}\right) = \frac{10^6\ Btu}{10^3 \frac{W}{kW} \bullet EER_D\ \left(\frac{Btu}{Wh}\right)} \bullet Electric\ Energy\ Cost\ \left(\frac{\$}{kWh}\right) \qquad (6.5)$$

with $C_{C,WSGHP}$ = cooling cost rate of WSGHPs (\$/MMBtu) and EER_D = energy efficiency ratio at design conditions. EER_D measures instantaneous cooling efficiencies of heat pumps. EER_D ratings can range from 12 to over 28, and depend on the entering water temperature (*EWT*) from the ground connection, as well as other performance parameters (IGSHPA, 2009).

The heating cost rate of WSGHPs is given by:

$$C_{H,WSGHP}\ \left(\frac{\$}{MMBtu}\right) = \frac{10^6\ Btu}{3{,}412 \frac{Btu}{kWh} \bullet COP_D} \bullet Electric\ Energy\ Cost\ \left(\frac{\$}{kWh}\right) \qquad (6.6)$$

with $C_{H,WSGHP}$ = heating cost rate of WSGHPs (\$/MMBtu) and COP_D = coefficient of performance. COP_D measures heating efficiencies of heat pumps. For WSHPs, COP_D can range from 3.5 to 5.0 depending on the *EWT* from the ground connection, and other performance parameters (IGSHPA, 2009). Energy costs and typical values for *SEER* and *AFUE* are listed in Tab 3C Economic Model Assumptions section and are obtained from the Energy Information Agency (EIA, 2015) and from IGSHPA (2009). Values for EER_D and COP_D are listed in Tab 3C Mechanical Equipment Selection Model Assumptions.

The total annual heating and cooling costs for BAU considers the yearly heating and cooling load based on the Climatic Model, and electricity and natural gas heating prices. For the geothermal installation, the total annual heating and cooling costs considers the yearly heating and cooling load, the number of heat pumps installed and their corresponding electricity consumption.

Table 6.8 - Economic Model Variables applied to the business-as-usual (BAU) scenario and to one geothermal field. The Model Variables section, in gray color, relates to equations and assumptions listed in the chapter and should not be modified.

ECONOMIC MODEL	
B. Model Variables	
Parameter	**Variables Information**
Cooling cost rate of an Air Conditioner/ASHP ($C_{C,ASHP}$) - ($/MMBtu)	25.0
Natural Gas Heating Rate for a Furnace or Boiler ($C_{H,fur}$) - ($/MMBtu)	18.4
Annual Estimated Energy Consumption for Business-as-Usual (Heating/Cooling) - (MMBtu/year)	11,601
Total Annual Heating/Cooling Cost for Business-as-Usual - ($)	235,556
Mechanical Equipment and Installation Cost for LOT A - ($)	425,000
Geothermal Loop Installation Cost for LOT A - ($)	403,956
Annual Electric Consumption of Water Source Heat Pumps in Heating Mode for LOT A - (MMBtu/year)	3,499
Heating Cost Rate of a Water Source Heat Pump ($C_{H,WSGHP}$) for LOT A - ($/MMBtu)	11
Annual Electric Consumption of Water Source Heat Pumps in Cooling Mode for LOT A - (MMBtu/year)	1,350
Cooling Cost Rate of a Water Source Heat Pump ($C_{C,WSGHP}$) for LOT A - ($/MMBtu)	10
Total Annual Electric Costs of Heat Pumps in Heating/Cooling Mode for LOT A - ($)	52,454

From Table 6.8, the annual estimated heating and cooling costs for BAU and for the GHP system are over $230,000 and $50,000, respectively. The GHPs energy consumption is much lower than the BAU case because the geothermal field in this example only provides around 50% of the total estimated peak heating load for all connected nodes.

The Mechanical Equipment and Installation Cost per geothermal field is calculated based on the mechanical equipment installation cost per ton, heat pump tonnage per unit, number of heat pump units installed, and costs for pumps, piping, and installation. The geothermal loop installation cost per field is calculated based on the total borehole design length and the loop installation cost per feet. Typical values for mechanical equipment and loop installation costs are listed in the Table 3C Model Assumptions section and vary depending on equipment selection and location characteristics.

In Table 6.9, an example of the Tab 3B Climatic Model section applied to the study area is provided. The section includes calculations for heating and cooling load per degree day, yearly heating and cooling load, and fraction of the year with cooling or heating load, as defined in equations 6.7 – 6.10.

The heating load per degree day is calculated as:

$$H_{DD} = \frac{Q_L \bullet 24}{(T_i - T_{o,H})} \tag{6.7}$$

with H_{DD} =heating load per degree day (Btu/DD), Q_L = total estimated heat load (Btu/hr), T_i = indoor design temperature (°F), and $T_{o,H}$ = outdoor heating design temperature (°F).

The cooling load per degree day is calculated as:

$$C_{DD} = \frac{Q_L \bullet 24}{(T_{o,C} - T_i)} \tag{6.8}$$

with C_{DD} = cooling load per degree day (Btu/DD), Q_L = total estimated heat load (Btu/hr), $T_{o,C}$ = outdoor cooling design temperature (°F), and T_i = indoor design temperature (°F). The total estimated heat load is obtained from the Tab 2B Heat Load & Distribution section. Typical values for indoor design temperatures and outdoor heating and cooling design temperatures are listed in the assumptions section and vary by location (CSU, 1978).

The yearly heating load is calculated as:

$$y_{L,H} = \frac{H_{DD} \bullet y_{H,DD}}{1{,}000{,}000} \tag{6.9}$$

with $y_{L,H}$ = yearly heating load (MMBtu/year), H_{DD} = heating load per degree day (Btu/DD), and $y_{H,DD}$ = annual heating degree days (DD). The heating load per degree day is calculated by using equation 6.7, and the annual heating degree days for the study area are listed in the Tab 3C Climatic Model Assumptions section and varies by location (CSU, 1978).

The yearly cooling load is calculated as:

$$y_{L,C} = \frac{C_{DD} \bullet y_{C,DD}}{1{,}000{,}000} \tag{6.10}$$

with $y_{L,C}$ = yearly cooling load (MMBtu/year), C_{DD} = cooling load per degree day (Btu/DD) and $y_{C,DD}$ = annual cooling degree days (DD). The cooling load per degree day is calculated by using equation 6.8, and the annual cooling degree days for the study area are listed in the Tab 3C Climatic Model Assumptions section and varies by location (CSU, 1978). Finally, the fraction of the year with heating or cooling load considers the yearly heating or cooling load calculated using equations 6.9 and 6.10 over the total yearly load. From Table 6.9, the region is dominated by high heating loads, which occur about 70% of the year.

Table 6.9 - Climatic Model Variables applied to the BAU scenario and the geothermal field(s). The Model Variables section, in gray color, relates to primary equations and assumptions listed in the chapter and should not be modified.

CLIMATIC MODEL	
B. Model Variables	
Parameter	**Variables Information**
Yearly Heating Load ($y_{L,H}$) - (MMBtu/year)	8,230
Heating Load per Degree Day (H_{DD}) - (Btu/DD)	1,209,789
Fraction of the Year for Heating Load	0.7
Yearly Cooling Load ($y_{L,C}$) - (MMBtu/year)	3,371
Cooling Load per Degree Day (C_{DD}) - (Btu/DD)	6,129,600
Fraction of the Year for Cooling Load	0.3

In Tables 6.10 – 6.13, examples of the Tab 3C Model Assumptions for the mechanical equipment selection, geothermal loop installation, and economic and climatic models applied to the study area are provided. The assumptions consider performance data for specific heat pump equipment, and regional characteristics for geology, climate, and energy prices compiled from various sources of information.

In Table 6.10, performance data on the mechanical equipment selected for space heating and cooling applications is provided from submittal sheets (ClimateMaster, 2015; 2016). The data includes heat pump brand and model, heat pump installed capacity (tonnage), COP_D, entering and leaving water temperatures, flow rates, and electric consumption, among other data. Performance data for a range of operating temperatures is provided in Table B.2 of Appendix B for the selected heat pump model provided in this example (ClimateMaster, 2015; 2016). Submittal sheets vary for different heat pump brands and models based on the performance of the refrigeration cycle and the heat exchangers within the units. The user may modify the heat pump brand, model, and performance data to reflect preferred heat pump equipment.

Table 6.10 – Mechanical Equipment Model Assumptions based on equipment submittal sheets.

MECHANICAL EQUIPMENT SELECTION - Tranquility Modular Water-to-Water (TMW) Size 840	
C. Model Assumptions	
Parameter	**Assumptions Information**
Heat Pump Brand/Model	ClimateMaster/TMW840 Large Series
Heat Pump Tonnage - (Tons)	70
Heat Pump Coefficient of Performance (COP_D) in Heating Mode - (-)	3.6
Source Entering Water Temperature ($EWT_{S,H}$) in Heating Mode- (˚F)	30
Source Leaving Water Temperature ($LWT_{S,H}$) in Heating Mode - (˚F)	25
Source Flow Rate of Heat Pump - (GPM_S)	210
Load Flow Rate of Heat Pump - (GPM_L)	210
Density (ρ_{fluid}) of Heat Exchanger Fluid - (kg/m^3)	1060
Load Entering Water Temperature ($EWT_{L,H}$) in Heating Mode - (˚F)	100
Load Leaving Water Temperature ($LWT_{L,H}$) in Heating Mode - (˚F)	106
Electric Consumption of Heat Pump Unit in Heating Mode - (kW)	55
Heating Capacity (HC_{HP}) of the Heat Pump Unit in Heating Mode - (Btu/hr)	669,400
Heat of Extraction (HE_{HP}) of the Heat Pump in Heating Mode - (Btu/hr)	482,100
Heat Pump Coefficient of Performance (EER_D) in Cooling Mode - (-)	15
Source Entering Water Temperature ($EWT_{S,C}$) in Cooling Mode - (˚F)	90
Source Leaving Water Temperature ($LWT_{S,C}$) in Cooling Mode - (˚F)	99
Load Entering Water Temperature ($EWT_{L,C}$) in Cooling Mode - (˚F)	50
Load Leaving Water Temperature ($LWT_{L,C}$) in Cooling Mode - (˚F)	43
Electric Consumption of Heat Pump Unit in Cooling Mode - (kW)	52
Cooling Capacity (CC_{HP}) of the Heat Pump Unit in Cooling Mode - (Btu/hr)	749,300
Heat of Rejection (HR_{HP}) of the Heat Pump in Cooling Mode - (Btu/hr)	925,800

From Table 6.10, the equipment selected for this example is a 70-ton ClimateMaster Tranquility Modular Water-to-Water heat pump (TMW840) (ClimateMaster, 2015; 2016). From the ClimateMaster submittal sheets, the source entering water temperature ($EWT_{S,H}$) in heating mode from the geothermal connection in heating mode is 30 °F. In heating dominated climates, typical $EWT_{S,H}$ values for heating mode can range from 25 – 40 °F, and are generally 15 – 20 °F below the estimated ground temperature at the installation site (IGSHPA, 2009).

The source leaving water temperature ($LWT_{S,H}$) in heating mode is computed as follows:

$$LWT_{S,H} = EWT_{S,H} - \frac{HE_{HP}}{500 \bullet GPM_S} \tag{6.11}$$

with $LWT_{S,H}$ = source leaving water temperature in heating mode (°F), $EWT_{S,H}$ = source entering water temperature in heating mode (°F), HE_{HP} = heat of extraction of the heat pump in heating mode (Btu/hr), and GPM_S = source flow rate of the heat pump (GPM) (IGSHPA, 2009; ClimateMaster, 2015; 2016).

Approximately, a flow rate of 2 – 3 GPM per nominal ton is required for heat pumps. For WSGHPs, a flow rate of 3 GPM per nominal ton is recommended for both the source and load flow rates. The load entering water temperature ($EWT_{L,H}$) from the conditioned space in heating mode is 100 °F. Typical $EWT_{L,H}$ in heating mode are specified by the heat pump operator based on climatic and geologic characteristics of the site and range from 60 – 130 °F (IGSHPA, 2009).

In cooling mode, the source entering water temperature ($EWT_{S,C}$) from the geothermal connection is 90 °F. Typical $EWT_{S,C}$ values in cooling mode are generally 30 – 40 °F above the estimated ground temperature at the installation site (IGSHPA, 2009).

The source leaving water temperature ($LWT_{S,C}$) in cooling mode is computed as follows:

$$LWT_{S,C} = EWT_{S,C} + \frac{HR_{HP}}{500 \bullet GPM_S} \tag{6.12}$$

with $LWT_{S,C}$ = source leaving water temperature in cooling mode (°F), $EWT_{S,C}$ = source entering water temperature in cooling mode (°F), and HR_{HP} = heat of rejection to the ground connection in cooling mode (Btu/hr) (IGSHPA, 2009; ClimateMaster, 2015; 2016).

The $EWT_{L,C}$ from the conditioned space in cooling mode is 50 °F. Typical $EWT_{L,C}$ in cooling mode range from 30 – 80 °F and are specified by the heat pump operator. For both heat pump heating and cooling modes, the heat of extraction (HE_{HP}) and rejection (HR_{HP}), load leaving water temperatures (LWT_L), electric consumptions, efficiencies (COP_D, EER_D), and capacities are obtained from equipment submittal sheets based on the EWT_s, EWT_L, and source and load flow rates (GPM) (IGSHPA, 2009; ClimateMaster, 2015; 2016).

In Table 6.11, assumptions for sizing the geothermal loop installation are provided. Specifically, the minimum bore-to-bore spacing, estimated temperature of the ground (T_G), thermal conductivities of the ground (K_G) and grout (K_{GROUT}), ground loop thermal resistance in heating mode ($R_B+R_G \cdot F_H$), and diameter of the geothermal bore (D_B) and U-bend pipe (D_P) are provided. In geothermal loop installation design, bores are typically spaced between 15 to 20 feet apart to minimize thermal interference between bores. A minimum bore-to-bore spacing of 15 feet is recommended and assumed in this example (GHPC, 2004; IGSHPA, 2009).

The temperature of the ground can be estimated either through a formation thermal response test (TRT), or by assuming that the far-field temperature of the ground approximates the mean annual surface temperature at a site. A TRT provides information of the ground's thermal conductivity and diffusivity and undisturbed formation temperature at a site. The ground thermal conductivity can be estimated with a TRT or through literature sources of the expected subsurface rock types (GHPC, 2004; IGSHPA, 2009).

In vertical borehole loop configurations, grout is often used to provide thermal contact between the borehole and the surrounding rocks. In addition, grout provides structural stability to the borehole, controls groundwater movement around the borehole, and protects groundwater from any potential surface contamination (Allan and Philippacopoulos, 1999). Thermal conductivities of grout vary depending on the type and heat transfer characteristics. Standard bentonite grout has low thermal conductivity values ranging from 0.38 - 0.42 Btu/hr·ft·°F. Thermally enhanced grout can have thermal conductivity values of 0.6 – 1.0 Btu/hr·ft·°F (GHPC, 2004; IGSHPA, 2009).

Table 6.11 - Geothermal Loop Installation Design Model Assumptions.

GEOTHERMAL LOOP INSTALLATION DESIGN	
C. Model Assumptions	
Parameter	**Assumptions Information**
Minimum Bore-to-Bore Spacing - (feet)	15
Temperature of the Ground (T_G) - (˚F)	47.1
Thermal Conductivity of the Ground (K_G) - (Btu/hr ft ˚F)	1.3
Thermal Conductivity of the Grout (K_{GROUT}) - (Btu/hr ft ˚F)	1.0
Diameter of the Bore (D_B)- (inches)	5
Diameter of Nominal U-Bend Pipe (D_P) - (inches)	0.75
Run Fraction in Heating (F_H) - (-)	0.6
Ground Loop Resistance ($R_B + R_G \cdot F_H$) - (hr ft ˚F/Btu)	0.44

From Table 6.11, the diameter of the geothermal borehole (D_B) and nominal U-bend pipe (D_P) is 5 inches and 0.75 inches, respectively. Typically, borehole diameters can range from 4 – 6 inches, and U-bend pipe diameters are sized to 0.75 inches to accommodate the flow rate of 3 GPM per heat pump ton of installed capacity. The run fraction (F_H) in heating mode was estimated as 0.6 by using Figure B.1 in Appendix B (IGSHPA, 2009).

The run fraction estimates the annual ground loads for either heating or cooling dominated installations, which can have a significant effect on the geothermal loop design length. In this example, the run fraction estimate of 0.6 assumes that the geothermal heat pump system is sized to handle 100% of the design heating load (peak load) of the area, which has over 6,800 heating degree days (HDD). With estimates on the thermal conductivity of the ground and grout and the run fraction for heating, the ground loop resistance of 0.44 hr·ft·°F/Btu was approximated by using Table B.1 in Appendix B (IGSHPA, 2009).

In Table 6.12, Economic Model Assumptions that include cost estimates for the geothermal loop installation, mechanical equipment and installation, annual operation and maintenance costs, and federal incentives for geothermal technologies are provided. The geothermal loop installation cost is estimated as $16 per linear foot drilled ($52/m) for vertical loop systems installed in the northeast U.S.A. Geothermal loop installation costs may vary by loop configuration, dominant geology, geographic location, building installation type, and drilling method, among others variables (Battocletti and Glassley, 2013).

Table 6.12 –Economic Model Assumptions applied to the BAU scenario and the geothermal fields.

ECONOMIC MODEL	
C. Model Assumptions	
Parameter	**Assumptions Information**
Geothermal Loop Installation Cost - ($/feet)	16
Mechanical Equipment Installation Cost - ($/ton)	2,000
Pumps, Piping & Installation Costs - ($)	5,000
Annual Maintenance Cost of the GHP - ($/year)	200
Expected Lifetime (y) of the GHP System- (years)	20
Inflation Rate (ir) - (-)	0.02
Discount Rate (dr) - (-)	0.05
Electricity Rate for Residential Consumption - ($/kWh)	0.18
Electricity Rate for Commercial Consumption - ($/kWh)	0.14
Efficiency of the Air Conditioner/ASHP (SEER) - (-)	7
Natural Gas Heating Cost - ($/thousand cu ft)	12.3
Efficiency of the Natural Gas Furnace (AFUE) - (%)	65
Incentives for GHP Residential Installations - (%)	30
Incentives for GHP Commercial Installations - (%)	10

Mechanical equipment cost is estimated at $2,000 per ton of heat pump capacity installed, and costs for circulation pumps, piping and installation is estimated at $5,000 (GHPC, 2004; Beckers, 2016). GHP systems can cost anywhere from $1,200 - $2,000 per ton of installed capacity depending on size, geologic conditions, and climatic conditions, among other variables (GHPC, 2004).

Operating and servicing the geothermal system requires electricity consumption and annual maintenance. GHP technology can last well over 20 years, and the ground loop connection can last well over 50 years. In this example, a conservative value of 20 years is assumed for operating and servicing the GHP system. Electricity prices for residential and commercial sectors is considered based on rates particular to the study area, and can be modified to reflect different case studies (EIA, 2015; Beckers, 2016). Annual maintenance costs are estimated at $200 per year throughout the lifetime of the system (Beckers, 2016).

Other financial assumptions considered in the Economic Model include inflation (*ir*) and discount rates (*dr*), and incentives for GHP technology installations. Inflation and discount rates are used to calculate the total cost of ownership (*TCO*) of the GHP system in the Tab 3D Model Output section. Existing and potential sources of incentives or rebates could result in favorable impacts on the feasibility of financing GHP systems for residential and commercial installations.

As of 2017, a federal tax credit of 30% and 10% of the total system cost was available for residential and commercial GHP installations, respectively. The Database of State Incentives for Renewables and Efficiency (DSIRE) operated by the North Carolina Clean Energy Technology Center at North Carolina State University hosts a number of existing incentives nationwide in both commercial and residential settings for the implementation of energy-efficient systems (DSIRE, 2017).

In Table 6.13, Climatic Model Assumptions that include ambient outdoor heating and cooling design temperatures, indoor design temperatures, and typical heating and cooling degree days are provided. Outdoor heating and cooling design temperatures are often used to calculate peak load used to adequately size HVAC or GHP systems. For this example, the outdoor heating and cooling design temperature is estimated at -6 °F and 85 °F, respectively. Typical heating and cooling degree days are estimated at 6,803 and 550, respectively, and the indoor design temperature is set to 70 °F. The assumptions illustrated in Table 6.13 would not apply to case studies located in different geographic regions (ASHRAE, 1980; NYSERDA. 2017a).

Table 6.13 – Climatic Model Assumptions considered in the Geothermal Model.

CLIMATIC MODEL	
C. Model Assumptions	
Parameter	**Assumptions Information**
Outdoor Heating Design Temperature ($T_{o,H}$) - (˚F)	-6
Outdoor Cooling Design Temperature ($T_{o,C}$) - (˚F)	85
Indoor Design Temperature (T_i) - (˚F)	70
Typical Annual Heating Degree Days ($y_{H,DD}$) (Syracuse) - (-)	6,803
Typical Annual Cooling Degree Days ($y_{C,DD}$) (Syracuse) - (-)	550

In Table 6.14, an example of the Tab 3D Model Output from applying the Geothermal Model to the study area is provided. Specifically, summary results of the heating ratio provided by the GHP system and the associated costs, including capital costs (CAP), lifetime operation and maintenance costs (LOM), and total cost of ownership (TCO) of the GHP system are discussed.

Table 6.14 - Model Output from applying the Geothermal Model to the study area.

D. Geothermal Model Output	
Parameter	**Output Information**
Heating Ratio of GHP to Heat Load Demand at Design Conditions for LOT A - (%)	52
Capital Cost (CAP) for LOT A - ($MM)	0.8
Potential Commercial Federal Tax Credits for LOT A - ($M)	82.9
Lifetime Operation and Maintenance Costs (LOM) for LOT A - ($MM)	0.8
Total Cost of Ownership (TCO) for LOT A - ($MM)	1.5

From Table 6.14, the heating ratio of the GHP system to the heat load demand represents the total GHP heating capacity at design conditions divided by the total estimated heat load demand of the study area. In this example, the heating ratio of around 50% covers only half of the estimated total peak heating load of the area. However, the geothermal system could still provide for 80 - 90% of the annual heating energy requirements of the area (IDHA, 1983; Emeish, 1999). To increase the heating ratio to cover a larger demand, more geothermal fields would be required. Increasing the number of geothermal fields would also require additional equipment that increases overall capital, operating, and maintenance costs of the system.

The total CAP costs of the geothermal system is around \$800,000, and includes the mechanical equipment and installation costs, and the loop installation costs described in the Tab 3B Economic Model Variables section. The commercial federal tax credit only considers the current tax credit of 10% available for commercial installations. However, other potential sources of incentives or rebates might be applicable and are available through the DSIRE website described in the Tab 3C Economic Model Assumptions section. In this example, a commercial federal tax credit of 10% for the GHP system can save up to \$83,000.

The LOM costs and TCO of the geothermal field(s) for the expected lifetime of the system (20 years) is calculated by using the life cycle cost financial performance metric computed as follows:

$$TCO = \sum_{y=0}^{lt} \frac{CF_y}{(1+dr-ir)^y} \tag{6.13}$$

with TCO = total cost of ownership (\$MM), CF_y = cash flow in year y (\$), lt = expected lifetime of the system (20 years), $dr - ir$ = net discount rate, where dr = discount rate and ir = inflation rate. It is assumed that the CAP costs of the geothermal system are incurred in year zero (y = 0). The costs incurred during the subsequent years (y = 1 – 20) represent the annual operation and maintenance costs (Beckers, 2016). The annual operation and maintenance costs include electricity costs for operating the GHPs and maintenance costs for servicing the system.

Tab 4. GeoDistrict Energy Model

The GeoDistrict Energy Model applies technical and economic principles to offer a first-order approximation of the costs of distributing geothermal heat around a community with district energy networks. Similar to the Geothermal Model in Tab 3, the overall analysis workflow of the GeoDistrict Model consists of four major sections: A. Designer Input; B. Model Variables; C. Model Assumptions; and D. Model Output. In Table 6.15, a detailed description and user instructions are provided for the four major sections of the GeoDistrict Model.

The Tab 4A Designer Input section summarizes the energy production, distribution, and consumption systems of the model. In the GeoDistrict Model, the Designer Input section should not be populated because it summarizes input data and results from tabs 2 and 3, Heat Load & Distribution and Geothermal Model, respectively. Specifically, the Energy Production System in the Designer Input section is transferred from the Tab 3D Geothermal Model Output section. The Energy Distribution and Consumption Systems summarize and describe distribution nodes, distances from heat central to the nodes, and total heat load consumption per node previously defined in Tab 2, Heat Load & Distribution.

The Tab 4B Model Variables section includes principal design equations for the energy production, distribution, and consumption systems, and the economic and climatic models. The Energy Production System Model Variables describe the total energy produced by the geothermal field(s) and the additional energy required, if any, to meet the total estimated design heat load of the study area. For the examples provided in this section, it is assumed that any additional energy required to meet peak load will be provided with a natural gas peak boiler. However, future case studies could consider meeting peak load with a combination of geothermal resources and a biomass peak boiler.

The Energy Distribution System Model Variables include pumping energy, pipeline network pressure losses, thermal conductivity and heat losses, and temperature losses by pipe size and insulation series. The Energy Consumption System Model Variables include installed heat pump capacity and heat pump sizing at design load conditions for all consumers connected to the GSDE system.

The Economic Model Variables include pump and pipeline installation costs, annual maintenance and operation costs, and total cost of ownership throughout the expected lifetime of the system (20 years). In addition, estimates for the consumers' mechanical equipment and operation costs, annual energy cost savings from replacing inefficient heating and cooling systems with efficient heat pump systems, and estimated payback period is provided. The Climatic Model Variables include yearly heating and cooling load calculations based on heating and cooling degree days. The Tab 4B Model Variables for the GeoDistrict Model should not be populated, and should only be modified if the user elects to change the principal design equations.

The Tab 4C Model Assumptions section includes data collected from various sources on mechanical equipment selection, pipeline material thermal properties, and economic and climatic characteristics of the study area. Mechanical equipment data for various heat pump sizes and applications (residential versus commercial) was collected from available submittal sheets. Pipeline material thermal properties include thermal conductivities for steel, polyurethane (PUR) insulation, high-density polyethylene (HDPE) casing, sand, and soil, which encase the geothermal fluid distributed around the community.

The Economic Model Assumptions section includes installation, maintenance, and operation costs of pumps and pipes, energy costs, and inflation and discount rates. The Climatic Model Assumptions section includes outdoor heating and cooling design temperatures, and typical heating and cooling degree days. The Tab 4C Model Assumptions section for the GeoDistrict Model should be modified if different mechanical equipment selection and pipe materials are preferred, and based on location and geologic characteristics of the study area.

The Tab 4D Model Output section summarizes costs for the energy production, distribution, and consumption systems of the GeoDistrict Model. For the Energy Production System Model Output, the installation, maintenance, operation, and total costs are summarized for operating the geothermal system and for any supplemental heat provided by the natural gas peak boiler. A summary of the pipeline distribution total cost by pipe size and insulation series is provided in the Energy Distribution System Model Output. For the Energy Consumption System Model Output, a summary of the total capital cost (CAP), lifetime operation and maintenance costs (LOM), annual energy cost savings (AECS), and payback period (PB) of installing heat pumps systems to replace inefficient heating and cooling systems is provided. Finally, an overall summary of the costs and payback period for the entire GSDE system is provided in the Tab 4D GeoDistrict Model Output.

Table 6.15 - GeoDistrict Energy Model section description and user instructions.

Tab 4. GeoDistrict Energy Model	Section Description and User Instructions
A. Designer Input	**Energy Production System:** percent of geothermal energy to cover heat load from Tab 3. Geothermal Model, and percent of additional energy production required to cover heat load when geothermal energy does not meet 100% of the peak load. **User SHOULD NOT populate fields**, but SHOULD populate the Designer Input section in Tab 2. Heat Load & Distribution and Tab 3. Geothermal Model.
	Energy Distribution System: distribution nodes, distances from heat central to nodes, and node descriptions from Tab 2. Heat Load & Distribution. **User SHOULD NOT populate fields,** but SHOULD populate the Designer Input in Tab 2. Heat Load & Distribution.
	Energy Consumption System: total heat load consumption for each node from Tab 2. Heat Load & Distribution. **User SHOULD NOT populate fields,** but SHOULD populate the designer input in Tab 2. Heat Load & Distribution.
B. Model Variables	**Energy Production System:** total energy produced by the geothermal field(s) and by additional natural gas peak boiler to meet 100% of the total estimated heat load. Fields relate to Model Variables in Tab 3. Geothermal Model. **User SHOULD NOT populate fields.**
	Energy Distribution System: pipeline network pressure losses and pumping energy, temperature losses by pipe size and insulation series, and thermal conductivity and heat losses by pipe size and insulation series. Fields relate to equations and assumptions listed in the chapter. **User SHOULD NOT populate fields.**
	Energy Consumption System: estimated heat pump capacity at design conditions and heat pump percent sizing in heating mode by distribution node. Fields relate to equations and assumptions listed in the chapter. **User CAN ONLY modify the Number of Heat Pump Units. User SHOULD NOT populate any other fields.**
	Economic Model: pump and pipeline installation costs, annual maintenance costs, total lifetime operation costs, total cost of ownership, consumers' mechanical equipment capital costs and operation costs, annual energy cost savings, and payback period for energy production, distribution, and consumption systems. Fields relate to equations and assumptions listed in the chapter. **User SHOULD NOT populate fields.**
	Climatic Model: yearly heating/cooling load, heating/cooling load per degree day, fraction of the year in heating/cooling load. Fields relate to equations and assumptions listed in the chapter. **User SHOULD NOT populate fields.**

Table 6.15 Continued – GeoDistrict Energy Model section description and user instructions.

Tab 4. GeoDistrict Energy Model	Section Description and User Instructions
C. Model Assumptions	**Energy Production, Distribution, and Consumption Systems:** costs for pipes and pumps installation and maintenance, energy costs, outdoor design temperatures, pipeline supply and return temperatures, ground temperatures, and pipeline material thermal conductivity. **User CAN modify fields based on location, geologic, and pipeline material characteristics.**
	Mechanical Equipment Selection: heat pump model and performance characteristics from submittal data sheets for heating/cooling operations. **User CAN modify fields based on heat pump submittal data and location characteristics.**
D. Model Output	**Energy Production System:** capital costs, lifetime operation and maintenance costs, and total cost of ownership for geothermal field(s) and peak natural gas boiler. **User SHOULD NOT populate fields.**
	Energy Distribution System: distribution costs by pipeline size and insulation series. **User SHOULD NOT populate fields.**
	Energy Consumption System: capital costs, total lifetime operation and maintenance costs, total cost of ownership, annual energy cost savings per node, and payback period per unit within each node. **User SHOULD NOT populate fields.**
	Overall Geothermal District Heating and Cooling Network: summary of the total energy production, distribution, and consumption costs, and estimated payback period for the geothermal district heating and cooling distribution network. **User SHOULD NOT populate fields.**

In Table 6.16, an example of the Tab 4A Designer Input section applied to one geothermal field is provided. In this example, the Energy Production System for the study area covers around 52% of the estimated annual peak heat load with geothermal resources and around 48% with a natural gas peak boiler. Other case studies might take advantage of additional geothermal fields to cover a larger percentage of the annual peak load, reducing the need for additional energy production from fossil fuels. The Energy Distribution and Consumption systems summarize input data from Tab 2, Heat Load & Distribution. Additional node input information should only be populated in Tab 2.

Table 6.16 - GeoDistrict Energy Model Designer Input section for Energy Production, Distribution, and Consumption systems summarized from tabs 2 and 3 Heat Load & Distribution and Geothermal Model, respectively. The areas in gray color should not be populated.

ENERGY PRODUCTION SYSTEM						
A. Designer Input - Energy Production Required						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Percent Total Energy Produced (%)
Percent of Geothermal Energy to cover heat load (%)	52	0	0	0	0	52
Percent of Additional Energy Production to cover heat load with Natural Gas Boiler (%)						48
						100

ENERGY DISTRIBUTION SYSTEM								
A. Designer Input - Distances from Heat Central								
Nodes	Distance (ft)	Description	Nodes	Distance (ft)	Description	Nodes	Distance (ft)	Description
Node 1	188	Commercial (Large)	Node 8	0	0	Node 15	0	0
Node 2	134	Commercial (Mid)	Node 9	0	0	Node 16	0	0
Node 3	187	Commercial (Small)	Node 10	0	0	Node 17	0	0
Node 4	944	Residential	Node 11	0	0	Node 18	0	0
Node 5	0	0	Node 12	0	0	Node 19	0	0
Node 6	0	0	Node 13	0	0	Node 20	0	0
Node 7	0	0	Node 14	0	0	Node 21	0	0
							Total Pipeline Distribution Length (ft)	1,248
							Total Pipeline Distribution Length (m)	380

ENERGY CONSUMPTION SYSTEM								
A. Designer Input - Building Heat Loads								
Nodes	Total Node Heat Load (Btu/hr)	Description	Nodes	Heat Load (Btu/hr)	Description	Nodes	Heat Load (Btu/hr)	Description
Node 1	1,663,000	Commercial (Large)	Node 8	-	0	Node 15	-	0
Node 2	1,025,000	Commercial (Mid)	Node 9	-	0	Node 16	-	0
Node 3	143,000	Commercial (Small)	Node 10	-	0	Node 17	-	0
Node 4	1,000,000	Residential	Node 11	-	0	Node 18	-	0
Node 5	0	0	Node 12	-	0	Node 19	-	0
Node 6	0	0	Node 13	-	0	Node 20	-	0
Node 7	0	0	Node 14	-	0	Node 21	-	0
							Total Building Heat Load (Btu/hr)	3,831,000

In Table 6.17, an example of the Tab 4B Model Variables section for the Energy Production System is provided for one geothermal field and for the natural gas peak boiler. The geothermal field and natural gas boiler produce over 2 MMBtu/hr and over 1.8 MMBtu/hr, respectively. The energy produced from each geothermal field(s) is summarized from the total heat pump heating capacity at design conditions in the Geothermal Model Output (Tab 3B). The total energy produced from the natural gas peak boiler is obtained by multiplying the total estimated heat load for all nodes (Tab 3A in the Geothermal Model Designer Input) by the percent of additional energy production required to cover the annual load (Tab 4A in the GeoDistrict Model Designer Input).

Table 6.17 - Energy Production System Model Variables summarizing the total energy produced by the geothermal field(s) and by the natural gas peak boiler to provide for the estimated annual peak heat load of the study area.

ENERGY PRODUCTION SYSTEM						
B. Energy Production Variables - Total Energy Produced						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Energy Produced (Btu/hr)
Geothermal Energy Produced (Btu/hr)	2,008,200	-	-	-	-	2,008,200
Natural Gas Peak Boiler Energy Produced (Btu/hr)						1,822,800
						3,831,000

In Table 6.18, the Tab 4B Model Variables for pipeline distribution losses, including pressure losses and required pumping energy, for different pipe size diameters are provided. The pipes considered in this study are pre-insulated steel pipes (Elisteel EN253) commonly used in district heating applications in Iceland and Germany. Elisteel EN 253 pipes can be used directly for buried hot water district heating networks, and are made from steel surrounded by polyurethane (PUR) insulation and polyethylene (PE) outer casing. In this example, the pipe diameters range from 4 – 20 inches in size (Set Pipes, 2013). To calculate pressure losses and pumping power for a range of pipe diameters, the fluid flow velocity in a circular pipe, Reynolds number, friction factor, and head loss were computed, as defined in equations 6.14 – 6.19.

The fluid flow velocity in the distribution pipe is computed as follows:

$$v_{DP} = 0.4085 \frac{\dot{V_{DP}}}{(D_{DP,i})^2} \tag{6.14}$$

with v_{DP} = fluid flow velocity in the distribution pipe (ft/sec), $\dot{V_{DP}}$ = volumetric flow rate in the distribution pipe (GPM), and $D_{DP,i}$ = inside diameter of the distribution pipe (in.).

To characterize the internal pipe flow regime, the Reynolds number calculates the ratio of inertial to viscous forces:

$$Re = 124 \frac{v_{DP} \bullet D_{DP,i}}{({}^{\mu_{DP}}/{}_{\rho_{fluid,DP}})} \tag{6.15}$$

with Re = dimensionless Reynolds number (-), v_{DP} = fluid flow velocity in the distribution pipe (ft/sec), $D_{DP,i}$ = inside diameter of the distribution pipe (in.), μ_{DP} = fluid viscosity in the distribution pipe (cP), and $\rho_{fluid,DP}$ = density of fluid in the distribution pipe (lb/ft^3).

Reynolds numbers less than 2,300 and greater than 2,500 are representative of laminar and turbulent flow, respectively. Reynolds numbers greater than 10,000 are representative of fully turbulent flow. To ensure maximum heat transfer in the geothermal circulating fluid, turbulent flow is desired in the ground-loop piping (IGSHPA, 2009).

The pipe friction factor used to calculate the head loss is computed using the Nikuradse equation:

$$f = 0.0032 + 0.221\, Re^{-0.237} \tag{6.16}$$

with f = dimensionless friction factor (-) for smooth pipes for Reynold's numbers (Re) greater than 10,000 calculated from equation 6.15 (Nikuradse, 1932; IGSHPA, 2009).

The head loss due to friction in the distribution pipes is calculated using the Darcy-Weisbach equation:

$$h_{f,DP} = L_{DP} \bullet f \bullet \left(\frac{1}{D_{DP,i}/12}\right) \bullet \frac{v_{DP}{}^2}{2g} \tag{6.17}$$

with $h_{f,DP}$ =head loss in the distribution pipes (ft.), L_{DP} = total pipeline distribution length (ft.), f = dimensionless friction factor (-) for smooth pipes, $D_{DP,i}$ = inside diameter of the distribution pipe (in.), v_{DP} = fluid flow velocity in the distribution pipe (ft/sec), and g = gravity constant (ft/s^2). Head loss is expected to decrease with increasing fluid temperatures and pipe sizes, and to increase with increasing fluid flow rates and viscosities (IGSHPA, 2009).

Furthermore, to determine the pressure loss in the pipes the following equation is used:

$$\Delta p_{,DP} = \gamma_{DP} \bullet h_{f,DP} \tag{6.18}$$

with $\Delta p_{,DP}$ = pressure loss in the distribution pipes (N/m^2 or Pa), γ_{DP} = specific weight of the fluid in the distribution pipe (N/m^3) where γ_{DP} = $\rho_{fluid,DP} \bullet g$, $\rho_{fluid,DP}$ = density of fluid in the distribution pipe (kg/m^3), g = gravity constant (m/s^2), and $h_{f,DP}$ =head loss in the distribution pipes (m) (Reber, 2013). In district heating design practices, the pipe diameter is selected to sustain pressure drops in the order of 50 – 100 Pa/m of pipe installed (Elíasson et al., 2003).

Finally, the pumping power is computed as follows:

$$P_{pump} = \Delta p_{,DP} \bullet \frac{\dot{m}_{DP}}{\rho_{fluid,DP}} \bullet \frac{1}{\eta} \tag{6.19}$$

with P_{pump} = pumping power (W), $\Delta p_{,DP}$ = pressure loss in the distribution pipes (N/m^2 or Pa), $\dot{m}_{DP}$ = mass flow rate in the distribution pipes (kg/s), $\rho_{fluid,DP}$ = density of fluid in the distribution pipe (kg/m^3), and η = pump efficiency (%).

Table 6.18 - Energy Distribution System Model Variables summarizing pipe head loss, pressure loss, and pumping power by pipe size diameter.

ENERGY DISTRIBUTION SYSTEM											
B. Energy Distribution Variables - Pipeline Network Distribution Losses - Pressure Losses and Pumping Energy											
Pipe Size (DN,mm)	Pipe Diameter (in)	Fluid Flow velocity (ft/s)	Reynolds Number (-)	Friction Factor (-)	Head Loss (ft)	Head Loss (m)	Head Loss (m/m)	Pressure Loss (N/m^2 or Pa)	Pressure Loss per m (Pa/m)	Pumping Power (W)	Pumping Power per m (W/m)
DN100	4	31	1.4E+06	0.011	595.3	181.4	0.48	1.8E+06	4638.2	1.9E+05	500.7
DN150	6	14	9.2E+05	0.012	84.0	25.6	0.07	2.5E+05	654.4	2.7E+04	70.6
DN200	8	8	6.9E+05	0.012	21.0	6.4	0.02	6.2E+04	163.3	6.7E+03	17.6
DN250	10	5	5.5E+05	0.013	7.1	2.2	0.01	2.1E+04	55.6	2.3E+03	6.0
DN300	12	3	4.6E+05	0.013	3.0	0.9	0.002	8.8E+03	23.1	9.5E+02	2.5
DN350	14	2	3.9E+05	0.014	1.4	0.4	0.001	4.2E+03	11.0	4.5E+02	1.2
DN500	20	1	2.8E+05	0.015	0.3	0.1	0.0002	7.5E+02	2.0	81	0.2

From the example in Table 6.18, pipe size DN250 results in a fully turbulent flow regime and a pressure drop in the order of 50 – 100 Pa/m. Pipe size DN250 has an internal diameter of roughly 10 inches (250 mm), and results in a pressure loss of around 56 Pa/m with a total pipeline pumping power of 2.3 kW or 6.0 W/m of pipe installed. For case studies that consider future district network expansions, selecting a larger pipe size prior to expansion might help accommodate growth of the GSDE system, which could save future capital costs and annual operation and maintenance costs.

To estimate pipeline network temperature losses from the heat central location to the consumer nodes, the thermal conductivity of the pipeline network and the heat loss per meter of pipe were assessed. From Figure 6.5, the pre-insulated pipes are placed in a trench about 0.7 m below the surface (2.3 ft.). Once the pipes are installed, a backfill sand layer of about 0.15 m (0.49 ft.) in thickness is used to cover and secure the pipes, followed by a soil layer of about 0.5 m (1.8 ft.) in thickness.

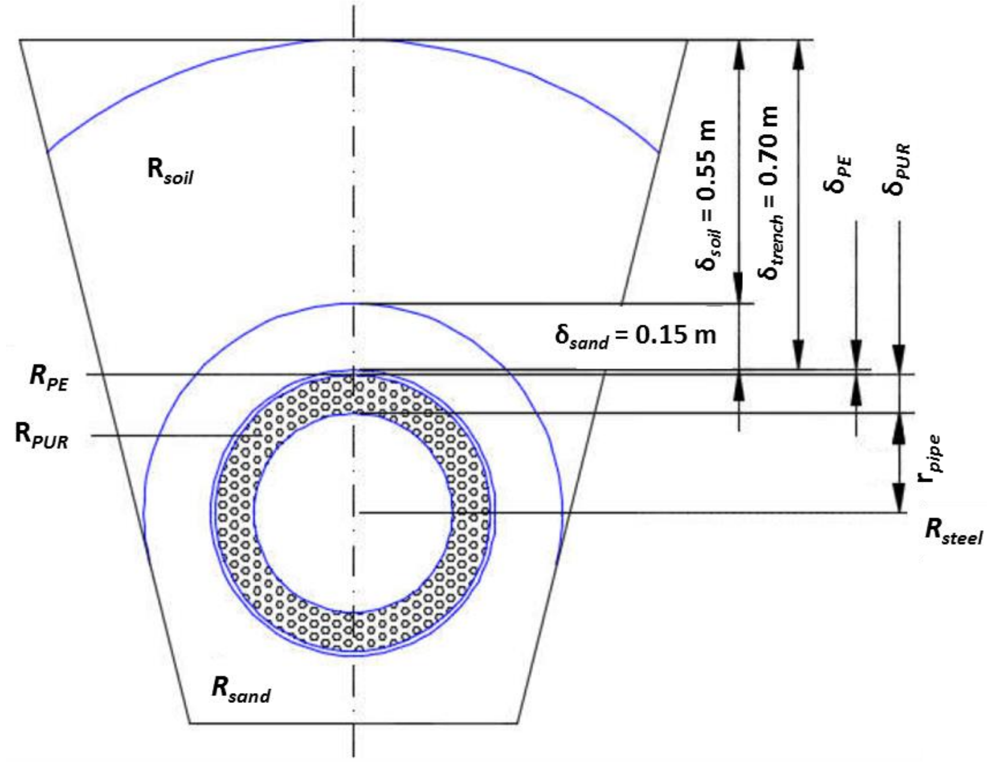

Figure 6.5 - Cross-section of the district heating pipe installation. The pipes are made of steel, polyurethane (PUR) insulation foam, and polyethylene (PE) casing pipe. The PUR and PE thicknesses, δ, and thermal resistances, R, depend on the insulation series. The pipe installation includes sand and soil backfill to cover and secure the pipes (Jóhannesson, 2016).

The pre-insulated Elisteel EN 253 district heating pipes can be purchased in lengths of 6, 12, or 16 m with insulation series 1, 2, or 3. The thicknesses (δ) of the PUR insulation foam and the PE casing vary depending on the insulation series. Insulation series 1 has thinner PUR foam and PE casing than series 2, and series 3 has the thickest PUR insulation foam and PE casing of all three series (Set Pipes, 2013; Jóhannesson, 2016).

From Figure 6.5, all of the materials used in district heating pipe installations have variable heat losses. To calculate the overall pipeline thermal conductivity (k_{pipe}) and heat loss (q_{pipe}), the thermal resistances (R) for each individual material were assessed as defined in equations 6.20 – 6.26 (Howard, 1996).

The thermal resistance of the steel pipe is computed as follows:

$$R_{steel} = \frac{ln(r_{steel}+\delta_{steel})-ln(r_{steel})}{2 \bullet \Pi \bullet K_{steel}} \tag{6.20}$$

with R_{steel} = thermal resistance of the steel pipe (m·K/W), r_{steel} = radius of the steel pipe (m), δ_{steel} = thickness of the steel pipe (m), and K_{steel} = thermal conductivity of the steel pipe (W/m·K). A typical thermal conductivity value of 50 W/m·K was assumed for steel pipes, and may vary for different pipe materials (Set Pipes, 2017).

The thermal resistance of the polyurethane insulation foam (PUR) is computed as follows:

$$R_{PUR} = \frac{ln(r_{steel}+\delta_{steel}+\delta_{PUR})-ln(r_{steel}+\delta_{steel})}{2 \bullet \Pi \bullet K_{PUR}} \tag{6.21}$$

with R_{PUR} = thermal resistance of the PUR insulation foam (m·K/W), δ_{PUR} = thickness of the PUR insulation foam (m), and K_{PUR} = thermal conductivity of the PUR insulation foam (W/m·K). For the PUR insulation thermal conductivity, a typical value of 0.026 W/m·K was assumed (Set Pipes, 2013; 2017).

The thermal resistance of the polyethylene (PE) casing pipe is computed as follows:

$$R_{PE} = \frac{ln(r_{steel}+\delta_{steel}+\delta_{PUR}+\delta_{PE})-ln(r_{steel}+\delta_{steel}+\delta_{PUR})}{2 \bullet \Pi \bullet K_{PE}} \tag{6.22}$$

with R_{PE} = thermal resistance of the PE casing pipe (m·K/W), δ_{PE} = thickness of the PE pipe (m), and K_{PE} = thermal conductivity of the PE pipe (W/m·K). A typical thermal conductivity value of 0.4 W/m·K was assumed for PE casing pipes (Set Pipes, 2013; 2017).

The steel pipe radii and thicknesses are obtained from product catalogue data provided in Table B.3 of Appendix B. In addition, the PUR and PE casing pipe thicknesses vary by insulation series 1, 2, or 3, and are provided in Table B.3 (Steel Pipes, 2013).

The thermal resistance of the sand backfill is computed as follows:

$$R_{sand} = \frac{ln(r_{steel}+\delta_{steel}+\delta_{PUR}+\delta_{PE}+\delta_{sand})-ln(r_{steel}+\delta_{steel}+\delta_{PUR}+\delta_{PE})}{2 \bullet \Pi \bullet K_{sand}} \tag{6.23}$$

with R_{sand} = thermal resistance of the sand backfill (m·K/W), δ_{sand} = thickness of the sand backfill (m), and K_{sand} = thermal conductivity of the sand backfill (W/m·K). The sand backfill thickness and thermal conductivity are assumed to be 0.15 m and 0.15 W/m·K, respectively (Jóhannesson, 2016).

The thermal resistance of the soil backfill is computed as follows:

$$R_{soil} = \frac{ln(r_{steel}+\delta_{steel}+\delta_{PUR}+\delta_{PE}+\delta_{sand}+\delta_{soil})-ln(r_{steel}+\delta_{steel}+\delta_{PUR}+\delta_{PE}+\delta_{sand})}{2 \bullet \Pi \bullet K_{soil}} \tag{6.24}$$

with R_{soil} = thermal resistance of the soil backfill (m·K/W), δ_{soil} = thickness of the soil backfill (m), and K_{soil} = thermal conductivity of the soil backfill (W/m·K). The soil backfill thickness and thermal conductivity are assumed to be 0.55 m and 1.2 W/m·K, respectively (Set Pipes, 2013; Jóhannesson, 2016).

Once the thermal resistances for all district heating pipe installation materials are characterized, the total buried pre-insulated distribution pipe thermal conductivity is calculated as:

$$K_{DP} = \frac{1}{R_{steel} + R_{PUR} + R_{PE} + R_{sand} + R_{soil}} \tag{6.25}$$

with K_{DP} = thermal conductivity of the buried pre-insulated distribution pipe (W/m·K), R_{steel} = thermal resistance of the steel pipe (m·K/W), R_{PUR} = thermal resistance of the PUR insulation foam (m·K/W), R_{PE} = thermal resistance of the PE casing pipe (m·K/W), R_{sand} = thermal resistance of the sand backfill (m·K/W), and R_{soil} = thermal resistance of the soil backfill (m·K/W).

Finally, the heat loss (q_{DP}) per meter of buried pre-insulated distribution pipe is calculated as:

$$q_{DP} = K_{DP} \bullet T_{avg,DHW} \tag{6.26}$$

with q_{DP} =heat loss per meter of buried pre-insulated distribution pipe (W/m), K_{DP} = thermal conductivity of the buried pre-insulated distribution pipe (W/m·K), and $T_{avg,DHW}$ = average temperature of the district heating water (°C). The average temperature of the district heating water is $T_{avg,DHW}$ = $(\frac{T_{s,DHW} - T_{r,DHW}}{2})$ – $T_{avg,DHT}$, where $T_{s,DHW}$ = supply district heating water temperature to the consumption nodes (°C), $T_{r,DHW}$ = return district heating water temperature to the heat central location (°C), and $T_{avg,DHT}$ = average ground temperature of the district heating trench (°C). The supply and return district heating water temperatures represent the load leaving water temperature (LWT_L) and the load entering water temperature (EWT_L), respectively (see Table 6.10). From Table B.12 of Appendix B, the average ground temperature of the district heating trench ($T_{avg,DHT}$) for the study area was assumed to be 9 °C (48 °F).

In Table 6.19, an example of the pipeline network thermal conductivity and heat loss for pipe sizes DN200 – DN500 with insulation series 1, 2, and 3 is provided. As expected, insulation series 1 results in the highest pipeline thermal conductivity and heat loss due to thinner PUR insulation foam and PE casing pipe. Insulation series 3 has the thickest PUR insulation foam and PE casing of all three series, and results in the lowest pipeline thermal conductivity and heat loss.

According to Jóhannesson (2016), insulation series 2 and 3 should be selected if the price of heat loss is higher than \$0.085/kWh and \$0.250/kWh, respectively, and if high casing pipe temperatures are expected. In many cases, insulation series 1 result in the most economical selection; however, if the thermal conductivities of the sand and soil backfill are too low (< 1

W/m·K) the casing pipe temperatures may become too high and other insulation series should be considered (Jóhannesson, 2016).

Table 6.19 - Energy Distribution System Model Variables summarizing pipeline network thermal conductivity and heat loss by pipe size diameter for insulation series 1, 2, and 3.

Thermal Conductivity and Heat Loss, Insulation Series 1, Pipe Length = 16 m							
	Thermal Resistances, R						
	Steel Pipe	PUR Insulation Foam	PE Casing Pipe	Sand Backfill	Soil Backfill	Total Pipeline Thermal Conductivity	Heat Loss
Pipe Size (DN,mm)	R_{steel} (m·K/W)	R_{PUR} (m·K/W)	R_{PE} (m·K/W)	R_{sand} (m·K/W)	R_{soil} (m·K/W)	K_{DP} (W/m·K)	q_{DP} (W/m)
DN200	1.3E-04	2.0	1.0E-02	0.7	0.1	0.4	4.5
DN250	1.1E-04	2.1	9.4E-03	0.6	0.1	0.4	4.5
DN300	1.1E-04	1.8	9.1E-03	0.5	0.1	0.4	5.2
DN350	9.9E-05	1.9	8.8E-03	0.5	0.1	0.4	5.1
DN500	7.8E-05	1.2	8.3E-03	0.4	0.1	0.6	7.6

Thermal Conductivity and Heat Loss, Insulation Series 2, Pipe Length = 16 m							
	Thermal Resistances, R						
	Steel Pipe	PUR Insulation Foam	PE Casing Pipe	Sand Backfill	Soil Backfill	Total Pipeline Thermal Conductivity	Heat Loss
Pipe Size (DN,mm)	R_{steel} (m·K/W)	R_{PUR} (m·K/W)	R_{PE} (m·K/W)	R_{sand} (m·K/W)	R_{soil} (m·K/W)	K_{DP} (W/m·K)	q_{DP} (W/m)
DN200	1.3E-04	2.7	1.0E-02	0.6	0.1	0.3	3.7
DN250	1.1E-04	2.8	9.1E-03	0.5	0.1	0.3	3.7
DN300	1.1E-04	2.5	8.8E-03	0.5	0.1	0.3	4.2
DN350	9.9E-05	2.6	8.4E-03	0.4	0.1	0.3	4.1
DN500	7.8E-05	1.9	8.0E-03	0.4	0.1	0.4	5.4

Thermal Conductivity and Heat Loss, Insulation Series 3, Pipe Length = 16 m							
	Thermal Resistances, R						
	Steel Pipe	PUR Insulation Foam	PE Casing Pipe	Sand Backfill	Soil Backfill	Total Pipeline Thermal Conductivity	Heat Loss
Pipe Size (DN,mm)	R_{steel} (m·K/W)	R_{PUR} (m·K/W)	R_{PE} (m·K/W)	R_{sand} (m·K/W)	R_{soil} (m·K/W)	K_{DP} (W/m·K)	q_{DP} (W/m)
DN200	1.3E-04	3.4	9.4E-03	0.6	0.1	0.2	3.1
DN250	1.1E-04	3.5	8.8E-03	0.5	0.1	0.2	3.1
DN300	1.1E-04	3.1	8.4E-03	0.4	0.1	0.3	3.5
DN350	9.9E-05	3.3	8.3E-03	0.4	0.1	0.3	3.4
DN500	7.8E-05	2.6	7.8E-03	0.3	0.1	0.3	4.2

Once the thermal conductivity of the buried pre-insulated distribution pipe is characterized by insulation series, the temperature of the district heating water leaving each consumption node is calculated as:

$$T_{N,DHW} = T_{avg,DHT} + (T_{s,DHW} - T_{avg,DHT}) \bullet exp \left(- \frac{K_{DP} \bullet L_N}{\dot{m}_{DP} \bullet c_{p,DP}}\right) \tag{6.27}$$

The temperature drop in the district heating pipes is calculated as:

$$\Delta t = T_{s,DHW} - T_{N,DHW} \tag{6.28}$$

with $T_{N,DHW}$ = temperature of the district heating water leaving each consumption node (°C), $T_{s,DHW}$ = supply district heating water temperature to the consumption nodes (°C), $T_{avg,DHT}$ = average ground temperature of the district heating trench (°C), K_{DP} = thermal conductivity of the buried pre-insulated distribution pipe (W/m·K), L_N = length of the distribution pipe from the consumption node to the heat central location (m), $\dot{m}_{DP}$ = mass flow rate in the distribution pipes (kg/s), $c_{p,DP}$ = specific heat capacity of the water in the distribution pipes (J/kg·K).

The mass flow rate ($\dot{m}_{DP}$) of the district heating water is the total volumetric flow rate of the district heating system times the density of the district heating water. The specific heat capacity of the district heating water ($c_{p,DP}$) was assumed to be 4200 J/kg·K (1.01 Btu/lb·°F) (see Table B.12 of Appendix B).

An example of the district heating water temperatures leaving the pipes at each consumption node and the temperature drop in the district heating pipes for sizes DN200 – DN500 with insulation series 1, 2, and 3 is provided in Table 6.20. From Table 6.20, the temperature drop in the district heating pipes for this example is negligible for all three insulation series because the consumption node distribution distances are small (<300 m). For the case studies in Section 6.4, analyses of the pipeline distribution losses and capital costs considering variations in insulation series and longer distribution nodes are provided.

Table 6.20 - Temperatures of the district heating water leaving each consumption node ($T_{N,DHW}$) and temperature drop (Δt) in pipelines by pipe size diameter for insulation series 1, 2, and 3.

Temperature Leaving the pipe at each consumer node, Insulation Series 1											
		Temperature Leaving the pipe (°C)					Temperature Drop in Pipelines (°C)				
Nodes	Distance, m	DN200	DN250	DN300	DN350	DN500	DN200	DN250	DN300	DN350	DN500
Node 1	57.2	41.33	41.33	41.33	41.33	41.33	2.1E-03	2.1E-03	2.4E-03	2.3E-03	3.5E-03
Node 2	40.8	41.33	41.33	41.33	41.33	41.33	1.5E-03	1.5E-03	1.7E-03	1.7E-03	2.5E-03
Node 3	56.9	41.33	41.33	41.33	41.33	41.33	2.1E-03	2.1E-03	2.4E-03	2.3E-03	3.5E-03
Node 4	287.8	41.32	41.32	41.32	41.32	41.32	1.0E-02	1.0E-02	1.2E-02	1.2E-02	1.8E-02

Temperature Leaving the pipe at each consumer node, Insulation Series 2											
		Temperature Leaving the pipe (°C)					Temperature Drop in Pipelines (°C)				
Nodes	Distance, m	DN200	DN250	DN300	DN350	DN500	DN200	DN250	DN300	DN350	DN500
Node 1	57.2	41.33	41.33	41.33	41.33	41.33	1.7E-03	1.7E-03	1.9E-03	1.9E-03	2.5E-03
Node 2	40.8	41.33	41.33	41.33	41.33	41.33	1.2E-03	1.2E-03	1.4E-03	1.3E-03	1.8E-03
Node 3	56.9	41.33	41.33	41.33	41.33	41.33	1.7E-03	1.7E-03	1.9E-03	1.9E-03	2.5E-03
Node 4	287.8	41.32	41.32	41.32	41.32	41.32	8.5E-03	8.5E-03	9.6E-03	9.4E-03	1.3E-02

Temperature Leaving the pipe at each consumer node, Insulation Series 3											
		Temperature Leaving the pipe (°C)					Temperature Drop in Pipelines (°C)				
Nodes	Distance, m	DN200	DN250	DN300	DN350	DN500	DN200	DN250	DN300	DN350	DN500
Node 1	57.2	41.33	41.33	41.33	41.33	41.33	1.4E-03	1.4E-03	1.6E-03	1.5E-03	1.9E-03
Node 2	40.8	41.33	41.33	41.33	41.33	41.33	1.0E-03	1.0E-03	1.1E-03	1.1E-03	1.4E-03
Node 3	56.9	41.33	41.33	41.33	41.33	41.33	1.4E-03	1.4E-03	1.6E-03	1.5E-03	1.9E-03
Node 4	287.8	41.33	41.33	41.33	41.33	41.32	7.1E-03	7.2E-03	8.0E-03	7.8E-03	9.7E-03

In Table 6.21, an example of the Tab 4B Energy Consumption Model Variables for four distribution nodes is provided. Individual water-to-water heat pump systems (WSGHP) connected to the distribution network would replace inefficient heating and air conditioning units within every building of each consumption node. The WSGHPs could provide for the space heating, cooling, and domestic hot water needs of each building.

Table 6.21 - Energy Consumption System Model Variables summarizing individual water-to-water heat pump (WSGHP) units connected to the distribution network.

B. Energy Consumption Variables - Estimated Heat Pump Capacity at Design Conditions							
Individual Building Water-to-Water Heat Pump Installations							
Nodes	Heat Load (Btu/hr) Per Unit	Description	ClimateMaster Heat Pump Series	ClimateMaster Heat Pump Tonnage (tons)	Number of Heat Pump Units (n)	Total Heat Pump Heating Capacity at Design Conditions (Btu/hr)	Heat Pump Sizing in Heating Mode (%)
Node 1	1,663,000	Commercial (Large)	ClimateMaster/TMW600 Large Series	50	3	1,540,500	93
Node 2	1,025,000	Commercial (Mid)	ClimateMaster/TMW340 Large Series	28	4	885,200	86
Node 3	143,000	Commercial (Small)	ClimateMaster/TMW060	5	3	149,100	104
Node 4	100,000	Residential	ClimateMaster/TMW036	3	4	110,800	111

From Table 6.21, the heat load per nodal unit is a designer input from Tab 2A (Heat Load & Distribution). The WSGHP series and size (tonnage) is based on equipment submittal sheets selected by the user to provide for the expected heat load per nodal unit. The heat pump heating capacity at design conditions will vary depending on the equipment series, size, and operating conditions specified by the user. Mechanical equipment selections for various heat pump models given a range of operating conditions are provided in Tables B.4 – B.11 of Appendix B. The number of heat pumps per nodal unit is a designer selection that determines the heat pump load sizing. The heat pump sizing determines if the selected equipment provides for the expected heat load per nodal unit.

From the example in Table 6.21, three heat pump units with an installed capacity of 50 tons would provide for over 90% of the total heat load for the building considered in node 1. Node 1 represents one large commercial building with an expected heat load of over 1.6 MMBtu/hr. Node 2 requires four 28-ton heat pumps to provide for over 85% of the commercial mid-size building heat load. Node 3 requires three 5-ton heat pumps to provide for over 100% of the small commercial building heat load. Node 4 represents a cluster of

10 residential homes each with a heat load of around 100,000 Btu/hr. The heat pump system for each building in node 4 is oversized by over 10% of the expected building heat load and required four 3-ton heat pump units.

According to IGSHPA, equipment should be sized to handle the greater of the peak heating or cooling load. In addition, equipment is generally sized to cover 75 – 100% of the peak heating load and 100% of the peak cooling load. For WSGHPs, oversizing of around 25% is recommended in either peak heating or cooling load design to allow for faster storage tank temperature recovery and "ramp up" operations (IGSHPA, 2009).

From Table 6.21, commercial buildings were sized to cover 75 – 100% of the peak heating load based on the assumption that peak heating load occurs before sunrise when commercial buildings are unoccupied. If needed, commercial buildings might cover peak load through supplemental heating with existing boilers (Bhatia, 2012). Residential buildings were only slightly oversized because, for this case, prior to new equipment installation extensive building retrofitting is expected to significantly reduce building heat load.

The Energy Distribution System Economic Model includes pump and pipeline installation costs, equipment operation and maintenance costs, and total cost of ownership of the distribution system. In Table 6.22, the Tab 4B Economic Model Variables for the pump and pipeline installation cost is provided for pipe sizes DN200 – DN500 with insulation series 1, 2, and 3.

From Table 6.22, the pump installation costs per pipe size represent the pump cost ($/kW) times the pumping power per m (W/m) from the pipeline pressure losses and pumping energies calculated in Table 6.18. The pump cost is assumed to be $150/kW (Reber, 2013;

Jóhannesson, 2016). The pipeline installation costs ($/m) vary by insulation series 1, 2, and 3, and include costs for pipes, fittings, trench excavation work, and engineering services, among other costs (Jóhannesson, 2016).

Table 6.22 - Energy Distribution System Model Variables summarizing the pump and pipeline installation costs.

Pump and Pipeline Installation Cost							
Pipe Size (DN,mm)	Pump Installation Cost ($/m)	Insulation Series 1, Pipeline Installation Cost ($/m)	Insulation Series 2, Pipeline Installation Cost ($/m)	Insulation Series 3, Pipeline Installation Cost ($/m)	Insulation Series 1, Total Pump + Pipeline Installation Cost ($/m)	Insulation Series 2, Total Pump + Pipeline Installation Cost ($/m)	Insulation Series 3, Total Pump + Pipeline Installation Cost ($/m)
DN200	2.64	149	174	199	152	177	201
DN250	0.90	204	240	270	205	241	270
DN300	0.37	238	281	316	238	281	317
DN350	0.18	276	328	378	276	328	378
DN500	0.03	418	505	646	418	505	646

The total pump and pipeline installation costs is the sum of the pump installation costs ($/m) and the pipe installation costs ($/m) for each pipe size and insulation series. As expected, the pump installation costs decrease with increasing pipe size because of lower pressure losses per meter of pipe installed. However, the total pump and pipeline installation costs are greater for larger pipe sizes and pipes with more insulation (series 2 and 3) because of the added material cost from larger and heavily insulated pipes.

The lifetime (20 years) operating and maintenance costs (LOM) and total cost of ownership (TCO) of the Energy Distribution System is calculated according to the life cycle cost financial performance metric described in equation 6.13. In Table 6.23, the LOM cost of the pumps and pipelines is provided for pipe sizes DN200 – DN500 with insulation series 1, 2, and 3. For operating the pumps, the annual pumping electricity cost ($/m/year) represents the pumping power (W/m) times the annual pump utilization power (hours/year) and the electricity rate.

The annual pump utilization power is assumed to be 8760 hours per year because the GSDE network will provide continuous space heating and cooling to the study area. The electricity rate for the commercial sector is assumed to be $0.14/kWh (EIA, 2015; Beckers, 2016). The annual maintenance costs for the pumps and pipelines are assumed to be 5% and 2% of the installation costs per year, respectively (Jóhannesson, 2016).

Table 6.23 - Energy Distribution System Model Variables summarizing the lifetime operating and maintenance cost of pumps and pipelines.

	Pump and Pipeline Lifetime Operating and Maintenance (20 years)			
Pipe Size (DN,mm)	**Annual Pump Operating Cost ($/m/yr)**	**Insulation Series 1, Pump and Pipeline Lifetime O&M Cost ($/m)**	**Insulation Series 2, Pump and Pipeline Lifetime O&M Cost ($/m)**	**Insulation Series 3, Pump and Pipeline Lifetime O&M Cost ($/m)**
DN200	21.4	341	348	355
DN250	7.3	170	181	190
DN300	3.0	116	129	139
DN350	1.4	104	119	134
DN500	0.3	128	154	196

From Table 6.23, the pump annual electricity operating cost per meter is higher for smaller pipe sizes and lower for larger pipe sizes due to larger pressure losses in smaller pipes. The lifetime pump operating costs are expected to be significant for smaller pipe sizes, and greater than the lifetime maintenance costs for both the pumps and pipelines. Pipe size DN200 results in the highest LOM costs for all insulation series, and pipe size DN350 results in the lowest, followed by pipe sizes DN300, DN500, and DN250.

In Table 6.24, the TCO throughout the lifetime of the system (20 years) for the distribution network is provided for pipe sizes DN200 – DN500 with insulation series 1, 2, and 3. The TCO includes costs of installation, operation, and maintenance of the pumps and pipelines. For each insulation series in Table 6.24, pipe sizes DN250 - DN350 result in lower

TCO, while pipe sizes DN200 and DN500 result in higher TCO due to high operating and installation cost, respectively.

Table 6.24 - Energy Distribution System Model Variables summarizing the total cost of ownership of pumps and pipelines.

	Pump and Pipeline Total Cost of Ownership (TCO)		
Pipe Size (DN,mm)	Insulation Series 1, Lifetime Pump and Pipeline Cost ($/m)	Insulation Series 2, Lifetime Pump and Pipeline Cost ($/m)	Insulation Series 3, Lifetime Pump and Pipeline Cost ($/m)
DN200	493	524	556
DN250	375	421	460
DN300	354	410	456
DN350	379	447	512
DN500	546	660	842

According to Elíasson et al. (2003), pipe sizes are selected to sustain pressure drops in the order of 50 – 100 Pa/m of pipe installed. From tables 6.18 and 6.24, pipe size DN250 is an adequate selection for this example as it could sustain a pressure drop of around 56 Pa/m and also result in the lowest TCO. If future district network expansion is considered, selecting a larger pipe size (DN300) might help accommodate for future growth in the GSDE network and could save future capital expenditures and annual operating and maintenance costs.

In Table 6.25, the Tab 4B Energy Consumption System Economic Model considers the capital (CAP) costs, TCO, annual energy cost savings (AECS), and payback period (PB) of individual building WSGHPs connected to the GSDE network. The CAP cost, LOM costs, and TCO for both the BAU scenario and the WSGHP installations follow equations 6.3 – 6.10 and 6.13, and methodology described in tables 6.8, 6.9 and 6.14 of the Geothermal Model section (Tab 3).

From Table 6.25, the payback period (PB) considers the CAP costs divided by the AECS from replacing the BAU heating and cooling equipment with WSGHPs. The AECS takes the difference between the total annual heating and cooling costs with BAU equipment and with WSGHPs. The electricity consumption of WSGHPs in heating or cooling mode depends on the performance (COP) and the heating capacity of the heat pumps at design conditions. A heat pump system operating at lower COPs will consume more electricity and result in less annual electricity cost savings when compared to the BAU system.

Table 6.25 - Energy Consumption System Model Variables summarizing the total cost of ownership and payback period for individual building water-to-water heat pump (WSGHP) installations.

B. Economic Model Variables - Individual Building Water-to-Water Heat Pump Installations							
Total Cost of Ownership ($) and Expected Payback Period (years) per Unit							
Nodes	Mechanical Equipment Cost Per Unit ($)	Potential Federal Tax Credit Per Unit ($)	Total Annual Electric Costs of Heat Pumps in Heating/Cooling Mode Per Unit ($)	Total Cost of Ownership Per Unit ($)	Total Annual Heating and Cooling Costs Per Unit Business-as-Usual ($)	Annual Energy Cost Savings Per Unit ($/year)	Simple Payback Period Per Unit (years)
Node 1	300,000	30,000	41,583	897,582	94,622	53,038	5
Node 2	224,000	22,400	27,275	619,280	58,321	31,046	6
Node 3	30,000	3,000	4,193	98,307	8,136	3,944	7
Node 4	24,000	7,200	3,792	85,121	6,149	2,356	7

From the example in Table 6.25, the PB for the units considered in nodes 1 – 4 ranges from 5 – 7 years. As expected, overdesigned heat pump systems (residential units in node 4) result in a PB that is higher than those systems designed to cover 75 – 100% of the peak heating load. Peak heating load generally occurs before sunrise when residential units are occupied and commercial units unoccupied. A slightly overdesigned system ensures that the design of the heating system is sufficient to provide for peak load in residential buildings during the coldest days of the year. In addition, heat pump systems with operating conditions that result in lower COPs, COP = 3.3 for node 2 versus COP = 3.5 for node 1, have slightly higher PB because of lower AECS when compared to the BAU scenario.

The Tab 4C GeoDistrict Model Assumptions considering mechanical equipment selection, piping materials, and economic and climatic parameters are listed in Table B.12 of

Appendix B. The Economic Model Assumptions include energy prices, financial metrics, cost for equipment installations, and distribution pumps and pipelines. Climatic Model Assumptions include indoor and outdoor heating and cooling design temperatures, as well as average ground surface temperatures and thermal conductivities. The assumptions are compiled from various sources of information and can be easily modified to represent a range of case studies.

In Tables 6.26 – 6.29, examples of the Tab 4D GeoDistrict Model Output applied to the study area are provided. Specifically, summary costs for the Energy Production, Distribution, and Consumptions Systems are discussed, and the estimated PB for the entire GSDE network is provided.

Table 6.26 - Energy Production System Model Output from applying the GeoDistrict Energy Model to the study area.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD(S) COSTS						
Capital Costs ($MM) (with incentives)	0.7	0.0	0.0	0.0	0.0	0.7
Lifetime Operating and Maintenance Costs (20 years) ($MM)	0.8	0.0	0.0	0.0	0.0	0.8
Geothermal Total Cost of Ownership (20 years) ($MM)	1.5	0.0	0.0	0.0	0.0	1.5
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						63,798
Lifetime Operating and Maintenance Costs (20 years) ($)						165,344
Boiler Total Cost of Ownership (20 years) ($MM)						0.2
Total Energy Production System Cost (20 years) ($MM)						1.8

From Table 6.26, a summary of the Energy Production System CAP and LOM costs and TCO for the geothermal field(s) and supplemental natural gas boiler is provided. For the geothermal field covering around 50% of the study area peak heat load, the TCO is around $1.5

million dollars. The geothermal field CAP and LOM costs are roughly equal, \$0.7 million dollars and \$0.8 million dollars, respectively. To cover the remaining peak heat load (~50%), a supplemental natural gas boiler is considered. The CAP and LOM costs for the natural gas boiler are over \$60,000 and \$165,000, respectively, and the TCO is around \$0.2 million dollars. The total energy production system cost considering the geothermal field and supplemental natural gas boiler is around \$1.8 million dollars.

In Table 6.27, a summary of the CAP costs and TCO for the entire distribution network considering a range of pipe sizes and insulation series is provided. The CAP costs includes the total pump and pipeline installation costs, and the TCO includes the CAP and LOM costs throughout the lifetime of the GSDE network (20 years).

Table 6.27 - Energy Distribution System Model Output from applying the GeoDistrict Energy Model to the study area.

D. ENERGY DISTRIBUTION SYSTEM - Model Output			
District Heating and Cooling Network - Summary of Distribution Costs			
Capital Costs for Entire Distribution Network (\$MM) by Pipe Sizes and Insulation Series			
Pipe Size (DN,mm)	Insulation Series 1	Insulation Series 2	Insulation Series 3
DN200	0.06	0.07	0.08
DN250	0.08	0.09	0.10
DN300	0.09	0.11	0.12
DN350	0.10	0.12	0.14
DN500	0.16	0.19	0.25
Total Cost of Ownership (20 years) for Entire Distribution Network (\$MM) by Pipe Sizes and Insulation Series			
Pipe Size (DN,mm)	Insulation Series 1	Insulation Series 2	Insulation Series 3
DN200	0.19	0.20	0.21
DN250	0.14	0.16	0.18
DN300	0.13	0.16	0.17
DN350	0.14	0.17	0.19
DN500	0.21	0.25	0.32

From Table 6.27, the CAP costs for the entire distribution network increases with increasing pipe sizes and insulation series. For all insulation series, the TCO is the highest for pipe sizes DN200 and DN500 due to the operating pumping costs from significant pressure losses in small pipes, and the added material costs for larger and heavily insulated pipes, respectively. In this example, pipe sizes DN250 and DN300 with insulation series 1, 2, or 3 would be adequate selections due to low CAP and LOM costs.

In Table 6.28, a summary of the CAP and LOM costs, TCO, AECS, and PB for the Energy Consumption System is provided. The Energy Consumption System considers installing individual building water-to-water heat pumps (WSGHP) connected to the GSDE network for the space heating and cooling needs of the area.

Table 6.28 - Energy Consumption System Model Output from applying the GeoDistrict Energy Model to the study area.

D. ENERGY CONSUMPTION SYSTEM - Model Output							
Energy Consumption System Analysis - Summary of Consumers Cost							
Total Cost of Ownership for Consumers ($M) and Payback Period (years)							
Nodes	Description	No. of Units	Total Node Capital Cost (with incentives) ($)	Total Node Lifetime (20 years) Operating and Maintenance Costs ($)	Total Node Lifetime (20 years) Cost of Ownership ($)	Total Node Annual Energy Cost Savings ($/year)	Payback Period (years) Per Unit
Node 1	Commercial (Large)	1	270,000	627,582	897,582	53,038	5
Node 2	Commercial (Mid)	1	201,600	417,680	619,280	31,046	6
Node 3	Commercial (Small)	1	27,000	71,307	98,307	3,944	7
Node 4	Residential	10	168,000	683,206	851,206	23,565	7
Total for All Consumers ($MM)			0.7	1.8	2.5	0.1	

From the example presented in Table 6.28, the PB for the buildings considered within each node ranges from 5 – 7 years per unit. Residential units have a higher PB because heat pump systems are slightly overdesigned (see Table 6.21). The TCO for all the buildings considered is around $2.5 million dollars, with CAP and LOM costs, and AECS around $0.7 million dollars, $1.8 million dollars, and $0.1 million dollars per year, respectively.

In Table 6.29, a summary of the costs and PB for the entire GSDE network considered in this example is provided. Assuming that the geothermal field covers around 50% of the peak heat load and the distribution pipe size and insulation series is DN250 series 2, the total CAP costs and TCO throughout the lifetime of the system (20 years) for the Energy Production, Distribution, and Consumption systems is around $1.6 million dollars and $4.4 million dollars, respectively. The estimated PB for the GSDE network is around 14 years, less than the expected lifetime of the system (20 years). Even though the expected lifetime of the GSDE network is assumed to be 20 years, GHP technology can last well over 20 years and the ground loop connection can last well over 50 years.

Table 6.29 - Summary of the total costs, payback period, and levelized cost of heat for the entire geothermal district energy (GSDE) network including the Energy Production, Distribution, and Consumption systems.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	1.8
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 2	0.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	2.5
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	4.4
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	0.8
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 2	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.7
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.6
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	14
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	1.0
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	380
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN250; Series 2 ($/m)	181
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.8
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.8
Total Lifetime Annual Energy Produced (MMBtu)	499041
Levelized Cost of Heat ($/MMBtu)	8.8

The levelized cost of heat was estimated by using the Standard Levelized Cost Model, which utilizes a discounted cash-flow methodology:

$$LCOH = \frac{C_{cap} + \sum_{y=0}^{lt} \frac{C_{O\&M}}{(1+dr-ir)^y}}{\sum_{y=0}^{lt} \frac{E_y}{(1+dr-ir)^y}} \quad (6.29)$$

with $LCOH$ = levelized cost of heat ($/MMBtu), C_{cap} = the total capital investment cost for the Energy Production, Distribution, and Consumption systems ($MM), $C_{O\&M}$ = the total lifetime

(20 years) operation and maintenance costs for the Energy Production, Distribution, and Consumption system ($MM), E_y = energy (heat) generation in year *y*, *dr* = discount rate, and *ir* = inflation rate (OECD/EIA, 2010; Reber, 2013; Beckers, 2016).

For the example presented in Table 6.29, the *LCOH* was estimated at $8.8/MMBtu. A competitive *LCOH* for direct-use low-grade (<120 °C) geothermal applications is between $6/MMBtu - $14/MMBtu (Beckers, 2016). The example outlined in this section indicates that a GSDE network within the study area is techno-economically feasible.

In Section 6.4, several case studies considering a range of building heat loads, geothermal fields, and district network distribution lengths are provided. The proposed case studies consider installing GSDE networks in parking lots and vacant lots within the downtown area of Utica, NY. Specifically, Section 6.4.4 provides a comparison of the technical and economic analyses for each of the case studies considered in sections 6.4.1 – 6.4.3.

Tab 5. Summary Graphs

Results of the Geothermal Energy and GeoDistrict Model Outputs presented in tabs 2 and 3 are graphically summarized in Tab 5 for the Energy Production, Distribution, and Consumption systems. For the Energy Production Model, the graphs summarize the percent of total energy produced by the geothermal field(s) and by the supplemental energy system, if needed, in order to cover the peak heating load of the area. In addition, the CAP and LOM costs and TCO for the geothermal field(s) and supplemental peak boiler are graphically summarized.

For the Energy Distribution Model, the graphs summarized in Tab 5 include heat losses, and pipe installation CAP and LOM costs for various pipe sizes and insulation series. The graphs summarized for the Energy Consumption Model include results for mechanical equipment cost, total annual electric costs of the heat pumps installed, lifetime energy cost savings from BAU scenario, and PB per nodal unit. Examples of summary graphs for various case studies are provided in Section 6.4.4.

Tab 6. Unit Conversions

Metric and English Engineering units are adopted in the analyses presented in tabs 2 – 4 of the Geothermal Model and GeoDistrict Energy Model. In Table 6.30, unit conversions are provided.

Table 6.30 - Unit Conversion Table included in the GeoDistrict Energy Model.

UNIT CONVERSIONS			
Quantity	**To convert from**	**Into**	**Multiply by**
Length	Feet	Meters	0.3048
	Centimeters	Inches	0.394
	Meters	Yards	1.09
	Kilometers	Miles	0.62
Area	Square meters	Square feet	10.8
	Hectares	Square meters	10^4
	Square miles	Acres	640
	Acres	Hectares	0.4047
	Square miles	Square kilometers	2.59
Mass	Pounds	Kilograms	0.454
	Tons (US)	Pounds	2000
	Tons (US)	Kilograms	907
	Tonnes (metric)	Kilograms	10^3
	Tonnes (metric)	Pounds	2205
Volume	Liters	Quarts	1.057
	Liters	US Gallons	0.264
	Liters	Imperial Gallons	0.22
	Barrel (oil)	Gallons	42
Flow rate	Gallons per minute	Cubic meters/second	6.31×10^{-5}
Energy	Btus	Calories	252
	Btus	Joules	1055
	Joules	Newton-meters or 1 kg m^2/s^2	1
	Joules	kWh	2.78×10^{-7}
	Btus	Foot-pounds force	778
	Kilowatt-hours	Btu	3412
	Thousand Cubic Feet	Therms	10.28
	Quads (10^{15} Btus)	Exajoules (10^{18} joules)	1.055
Power	hp or horsepower (US = 550 $lb_f ft/s$)	Kilowatts	0.746

6.4: GeoDistrict Energy Model Techno-Economic Analysis: Sustainable Development Case Studies in Utica, NY

A series of case studies applying the GeoDistrict Energy tool discussed in Section 6.3.1 were evaluated to determine the techno-economic feasibility of installing shallow geothermal (ground-source) district energy (GSDE) networks in downtown Utica. The case studies provided in sections 6.4.1 – 6.4.4 incorporate variations in building thermal energy demand and consumer distribution distances.

In Figure 6.6, three energy phases are considered for sustainable development of geothermal energy in downtown Utica. Phase 1 considers connecting a GSDE network with a small subset of commercial and residential buildings labeled as energy nodes. In phase 2, additional energy nodes adjacent to phase 1 are added to the analysis. Phase 3 considers connecting multiple energy nodes extending to neighborhoods outside of the study area.

The potential location of the geothermal field(s), heat central facility, and supply and return distribution lines are depicted in Figure 6.6. The geothermal field(s) are connected to a heat central facility where the supply and return distribution pipelines carry hot water to the connected customers. For all the case studies analyzed in this chapter, assumptions on the geothermal field(s) size and location were made based on available open spaces, including parking lots and/or vacant lots depicted in Figure 6.6.

As described in Section 6.3.1, the design of the geothermal field(s) depends on the number of energy nodes (consumers), annual peak heating load of the area, expected pipeline distribution heat losses, and amount of supplementary heating, if any, to cover peak load. The techno-economic performance of adding multiple energy nodes to the design of the GSDE network is assessed in phases 2 and 3 for the case studies provided in sections 6.4.1 – 6.4.4.

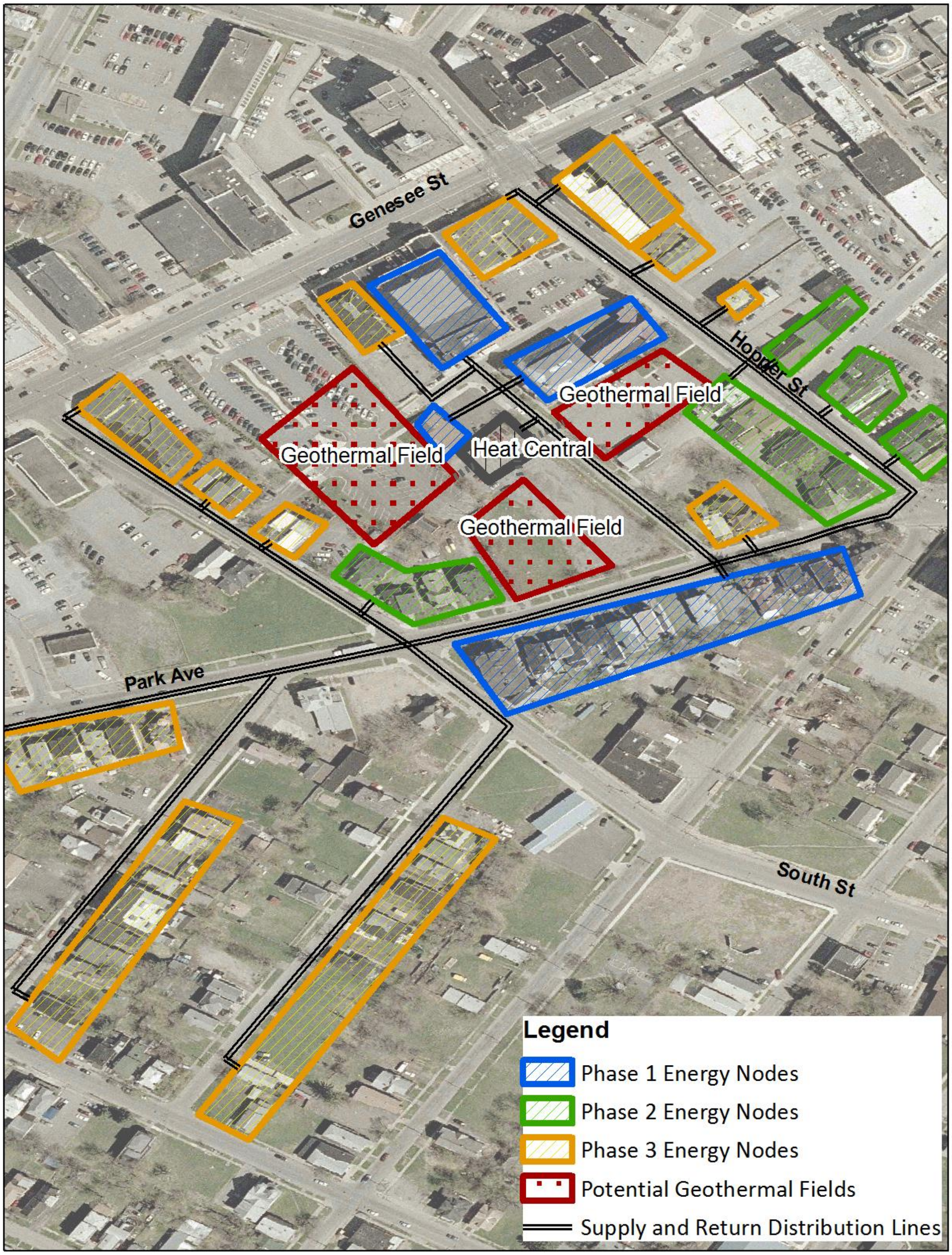

Figure 6.6 - Geothermal (ground-source) district energy (GSDE) sustainable development phases for downtown Utica, NY. Phase 1 considers a small subset of buildings connected to the GSDE network. Phases 2 and 3 consider additional energy networks.

The energy nodes in phase 1 consider the BAU scenario that includes three commercial buildings and 10 residential buildings from the sampled data in Section 6.2.1. For the study area in downtown Utica, the large commercial building is representative of the Stanley Theater, the mid-size commercial building represents the Tabernacle Church, and the small commercial building represents the Lotus Restaurant. The 10 residential buildings are representative of the residential units surveyed and modeled by Prathibha (2016). Phase 1 considers two scenarios: a. BAU heat load based on building data collection and energy load analyses (see Section 6.2.1); and b. 25% reduction in the BAU heat load from building retrofitting.

In Table 6.31, the building heat load demand and pipeline distribution distances for phase 1a considering BAU annual peak heating load is provided. From Table 6.31, the total estimated heat load for all energy nodes is over 3.8 MMBtu/hr. The total estimated pipeline distribution length for all nodes is over 1,200 feet.

Table 6.31 - Building heat loads and pipeline distribution lengths for phase 1a energy nodes considering business-as-usual (BAU) peak heating load.

Nodes	Description	No. of Units	Heat Load (Btu/hr) per unit	Total Node Heat Load (Btu/hr)	Distance from Heat Central (ft)
Node 1	Commercial (Large)	1	1,663,000	1,663,000	188
Node 2	Commercial (Mid)	1	1,025,000	1,025,000	134
Node 3	Commercial (Small)	1	143,000	143,000	187
Node 4	Residential	10	100,000	1,000,000	944

Total No. Units for all Nodes:	**13**
Total Estimated Heat Load (Btu/hr) for all Nodes:	**3,831,000**
Total Estimated Pipeline Distribution Length for all Nodes (ft):	**1,248**

In phase 1b, the effect of building heat load reductions from BAU on the GSDE network design is considered if energy conservation measures, such as the ones discussed in Section

6.2.2, achieve a lower heat load demand in the study area. A 25% reduction in the heat load demand for all residential and commercial buildings was considered for phase 1b scenario.

From Table 6.32, the total estimated heat load for all energy nodes is over 2.8 MMBtu/hr. Considering a 25% reduction in all building heat loads from the BAU scenario results in a 25% reduction of the total estimated heat load for all nodes from phase 1a scenario. Reductions in the area's annual peak heating load will require smaller geothermal field installation areas, resulting in lower capital costs and total cost of ownership, as well as shorter payback periods of the GSDE network.

Table 6.32 - Building heat loads and pipeline distribution lengths considering a 25% reduction in the BAU peak heat load demand for phase 1b energy nodes.

Nodes	Description	No. of Units	Heat Load (Btu/hr) per unit	Total Node Heat Load (Btu/hr)	Distance from Heat Central (ft)
Node 1	Commercial (Large)	1	1,247,250	1,247,250	188
Node 2	Commercial (Mid)	1	768,750	768,750	134
Node 3	Commercial (Small)	1	107,250	107,250	187
Node 4	Residential	10	75,000	750,000	944

Total No. Units for all Nodes:	**13**
Total Estimated Heat Load (Btu/hr) for all Nodes:	**2,873,250**
Total Estimated Pipeline Distribution Length for all Nodes (ft):	**1,248**

For the energy nodes in phase 2, a more aggressive energy conservation measure is considered for the buildings analyzed, and additional adjacent energy nodes are included in the case studies. A 50% reduction in all building heat loads would allow for more customer connections to the GSDE network with minimal impacts to the design of the geothermal fields, resulting in favorable technical and economic outputs.

The energy nodes of phase 2 include the nodes from phase 1 plus 12 additional residential buildings and 3 small commercial buildings. In Table 6.33, considering a 50% reduction in building heat loads demand and additional adjacent energy nodes, the total estimated heat load for all energy nodes is over 2.7 MMBtu/hr. The total estimated pipeline distribution length for all nodes is over 2,000 feet. Even with the addition of adjacent energy nodes, the total heat load demand for all energy nodes in phase 2 is lower than the load of phases 1a and 1b.

Table 6.33 - Building heat loads and pipeline distribution lengths considering a 50% reduction in the BAU peak heat load demand for phase 2 energy nodes.

Nodes	Description	No. of Units	Heat Load (Btu/hr) per unit	Total Node Heat Load (Btu/hr)	Distance from Heat Central (ft)
Node 1	Commercial (Large)	1	831,500	831,500	188
Node 2	Commercial (Mid)	1	512,500	512,500	134
Node 3	Commercial (Small)	1	71,500	71,500	187
Node 4	Residential	10	50,000	500,000	944
Node 5	Residential	5	50,000	250,000	1,115
Node 6	Residential	4	50,000	200,000	989
Node 7	Residential	3	50,000	150,000	831
Node 8	Commercial (Small)	2	71,500	143,000	942
Node 9	Commercial (Small)	1	71,500	71,500	1,072

Total No. Units for all Nodes:	**28**
Total Estimated Heat Load (Btu/hr) for all Nodes:	**2,730,000**
Total Estimated Pipeline Distribution Length for all Nodes (ft):	**2,021**

The energy nodes for phase 3 also consider a 50% reduction in building heat loads from BAU scenario plus the addition of multiple networks that extend beyond the original study area. Phase 3 includes the energy nodes from phases 1 and 2 plus additional residential buildings and several small-to-mid-size commercial buildings. In Table 6.34, considering a 50% reduction in building heat loads demand from BAU scenario plus the addition of multiple energy nodes, the total estimated heat load for all energy nodes is over 6.0 MMBtu/hr. The total estimated pipeline distribution length for all nodes is over 5,500 feet.

Table 6.34 - Building heat loads and pipeline distribution lengths considering a 50% reduction in the BAU peak heat load demand and multiple networks for phase 3 energy nodes.

Nodes	Description	No. of Units	Heat Load (Btu/hr) per unit	Total Node Heat Load (Btu/hr)	Distance from Heat Central (ft)
Node 1	Commercial (Large)	1	831,500	831,500	188
Node 2	Commercial (Mid)	1	512,500	512,500	134
Node 3	Commercial (Small)	1	71,500	71,500	187
Node 4	Residential	10	50,000	500,000	944
Node 5	Residential	2	50,000	100,000	482
Node 6	Residential	4	50,000	200,000	950
Node 7	Residential	5	50,000	250,000	1,115
Node 8	Residential	3	50,000	150,000	831
Node 9	Commercial (Small)	2	71,500	143,000	942
Node 10	Commercial (Small)	1	71,500	71,500	1,072
Node 11	Commercial (Small)	1	71,500	71,500	1,157
Node 12	Commercial (Small)	2	71,500	143,000	1,281
Node 13	Commercial (Mid)	2	512,500	1,025,000	1,474
Node 14	Commercial (Small)	2	71,500	143,000	1,485
Node 15	Commercial (Small)	1	71,500	71,500	366
Node 16	Commercial (Small)	1	71,500	71,500	1,115
Node 17	Residential	2	50,000	100,000	1,234
Node 18	Commercial (Mid)	1	512,500	512,500	1,483
Node 19	Residential	7	50,000	350,000	1,789
Node 20	Residential	8	50,000	400,000	1,722
Node 21	Residential	6	50,000	300,000	1,433

Total No. Units for all Nodes:	**63**
Total Estimated Heat Load (Btu/hr) for all Nodes:	**6,018,000**
Total Estimated Pipeline Distribution Length for all Nodes (ft):	**5,574**

The integration of multiple energy nodes to the GSDE network will require additional and/or larger geothermal fields and longer supply and return distribution lines because of the increase in the area's building heat load demand. The techno-economic performance of installing larger geothermal fields and adding multiple energy nodes to the GSDE network are addressed in sections 6.4.1 - 6.4.4.

Since annual peak heat load demand occurs only around 3 – 5% of the time, designing a geothermal system to cover between 50 – 70% of peak load can result economically viable and still provide for heating 80 – 90% of the time in a given year (Bloomquist, 2003; Boyd, 2009). To assess the techno-economic performance of the energy phases provided in Figure 6.6, geothermal fields were sized to cover 50%, 70%, or 100% of the area's annual peak heating load. Supplementary heating with a natural gas peak boiler is considered for geothermal fields that cover less than 100% of the annual peak heating load.

For all energy phases in Figure 6.6 and tables 6.31 – 6.34, the techno-economic performance of the geothermal fields providing around 50%, 70%, or 100% of the annual peak heating load are discussed in the case studies provided in sections 6.4.1 - 6.4.3. In Section 6.4.1, case study A evaluates the techno-economic performance of providing around 50% of the annual peak heating load with geothermal resources for all energy phases. Case studies B (Section 6.4.2) and C (Section 6.4.3) evaluate the techno-economic performance of geothermal resources providing around 70% and 100% of the annual peak heating load, respectively. A comparison of the capital costs, lifetime operating and maintenance costs, total cost of ownership, payback period, and levelized cost of heat for all energy phases of case studies A, B, and C is provided in Section 6.4.4.

6.4.1: Case Study A: Geothermal Resources Providing Around 50% of Annual Peak Heating Load

Phase 1a: Business-as-Usual (BAU) Peak Heating Load

For energy phase 1a in Table 6.31, four nodes with 13 individual units have a total estimated annual peak heating load of over 3.8 MMBtu/hr. The design of the district energy system to provide around 50% of the annual peak heating load of phase 1a with geothermal resources requires a field size of at least 105 feet long by 105 feet wide, resulting in an installation area of over 11,000 square feet.

From the Energy Production System in the GeoDistrict model, the geothermal field would require approximately 50 wellbores, each drilled to the maximum allowable depth of 450 m, and three 70-ton heat pumps to provide for over 2.0 MMBtu/hr (52% of phase 1a heat load). The remainder load of 1.8 MMBtu/hr (48% of phase 1a heat load) can be supplied with the natural gas peak boiler.

From the Energy Distribution System, a pipe size of DN250 results in a pressure loss of 56 Pa/m. Pipe size DN250 represents an adequate pipe diameter that ensures sustained pressure drops in the order of 50 – 100 Pa/m of pipe installed (Elíasson et al., 2003). When comparing the heat loss by insulation series for pipe size DN250, series 1, 2, and 3 lose around 4.5 W/m, 3.7 W/m, and 3.1 W/m, respectively. The total capital cost of insulation series 1, 2, and 3 for the total pipeline distribution length (>1,200 feet) is around $78,000, $92,000, and $103,000, respectively. For phase 1a of case study A, insulation series 3 for pipe size DN250 was selected to ensure minimal heat loss in the distribution pipes.

From the Energy Consumption System, the individual building water-to-water heat pump (WSGHP) for the large commercial building was sized to cover over 90% of the estimated annual peak heating load. The heat load for the large commercial building is over 1.6 MMBtu/hr, requiring at least three 50-ton heat pumps to cover 93% of the load. For the mid-sized commercial building, the heat load is over 1.0 MMBtu/hr, requiring at least four 28-ton heat pumps to cover over 85% of peak demand. For the small commercial building, three 5-ton heat pumps cover the entire estimated heat load of over 140,000 Btu/hr. For residential buildings with a heat load of 100,000 Btu/hr each, four 3-ton heat pumps cover over 110% of peak demand.

The Model Output for phase 1a of case study A is provided in tables 6.35 – 6.37. From Table 6.35, the capital costs (CAP), lifetime (20 years) operating and maintenance costs (LOM), and total cost of ownership (TCO) for the geothermal system that provides approximately 52% of phase 1a annual peak heating load is around \$0.7 million dollars, \$0.8 million dollars, and \$1.5 million dollars, respectively. For the natural gas peak boiler providing for the remainder 48% of phase 1a annual peak load, the CAP and LOM costs, and TCO are over \$63,000, \$165,000, and \$0.2 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating peak boiler throughout the lifetime of the GSDE network is around \$1.7 million dollars.

Table 6.35 – Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 1a of case study A. The Energy Production System covers around 52% of phase 1a annual peak heating load from geothermal resources and 48% of phase 1a annual heating load from a supplementary natural gas peak boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD(S) COSTS						
Capital Costs ($MM) (with incentives)	0.7	0.0	0.0	0.0	0.0	0.7
Lifetime Operating and Maintenance Costs (20 years) ($MM)	0.8	0.0	0.0	0.0	0.0	0.8
Geothermal Total Cost of Ownership (20 years) ($MM)	1.5	0.0	0.0	0.0	0.0	1.5
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						63,798
Lifetime Operating and Maintenance Costs (20 years) ($)						165,344
Boiler Total Cost of Ownership (20 years) ($MM)						0.2
Total Energy Production System Cost (20 years) ($MM)						1.7

In Table 6.36, the CAP costs, TCO, annual energy cost savings (AECS), and estimated payback period (PB) for the Energy Consumption System is provided. For phase 1a, the CAP cost for the installation of WSGHPs ranges from over $16,000 for residential buildings to around $270,000 for large commercial buildings. The PB ranges from 5 – 7 years per unit for all commercial and residential applications.

For the large commercial building, the CAP cost and TCO is around $270,000 and over $890,000, respectively. Furthermore, the AECS per year and PB for the large commercial building is around $50,000 per year and 5 years, respectively. For the mid-size commercial building, the CAP cost and TCO is over $200,000 and over $600,000, respectively. The AECS per year and PB is over $30,000 per year and 6 years, respectively. For the small commercial building, the CAP cost and TCO is around $27,000 and over $98,000, respectively. The AECS per year and PB is around $3,900 per year and 7 years, respectively.

Table 6.36 – Energy Consumption System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), total cost of ownership (TCO), total annual energy cost savings per year (AECS), and payback period (PB) for phase 1a of case study A.

D. ENERGY CONSUMPTION SYSTEM - Model Output							
Energy Consumption System Analysis - Summary of Consumers Cost							
Total Cost of Ownership for Consumers ($M) and Payback Period (years)							
Nodes	Description	No. of Units	Total Node Capital Cost (with incentives) ($)	Total Node Lifetime (20 years) Operating and Maintenance Costs ($)	Total Node Lifetime (20 years) Cost of Ownership ($)	Total Node Annual Energy Cost Savings ($/year)	Payback Period (years) Per Unit
Node 1	Commercial (Large)	1	270,000	627,582	897,582	53,038	5
Node 2	Commercial (Mid)	1	201,600	417,680	619,280	31,046	6
Node 3	Commercial (Small)	1	27,000	71,307	98,307	3,944	7
Node 4	Residential	10	168,000	683,206	851,206	23,565	7

For each residential building, the CAP cost and TCO is over $16,000 and over $85,000, respectively. The AECS per year and PB for each residential building is over $2,300 per year and 7 years, respectively. Because individual heat pump equipment for small commercial and residential buildings are slightly oversized, the payback periods for these buildings are longer than the large and mid-size commercial buildings.

A summary of the Total Energy Production, Distribution, and Consumption costs for the entire GSDE network of phase 1a is provided in Table 6.37. From Table 6.37, the CAP and LOM costs, and TCO for the GSDE network is $1.5 million dollars, $2.8 million dollars, and $4.4 million dollars, respectively. The AECS for all connected consumers to the GSDE network is around $0.1 million dollars per year, and the PB for the entire network is roughly 14 years. The payback period of 14 years is less than the estimated lifetime of the GSDE network (20 years).

The total lifetime annual energy produced is over 499,000 MMBtu resulting in a levelized cost of heat (LCOH) of $8.7/MMBtu. A competitive LCOH for direct-use low-grade (<120°C) geothermal applications is between $6/MMBtu - $14/MMBtu (Beckers, 2016). For phase 1a of case study A, the PB and LCOH indicate that a GSDE network within the study area is techno-economically feasible.

Table 6.37 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 1a of case study A.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	1.7
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	2.5
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	4.4
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	0.8
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.7
Sum of the Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.5
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	14
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	1.0
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	380
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN250; Series 3 ($/m)	190
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.8
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.8
Total Lifetime Annual Energy Produced (MMBtu)	499282
Levelized Cost of Heat ($/MMBtu)	8.7

Phase 1b: 25% Reduction in BAU Peak Heating Load

If energy conservation measures result in a 25% reduction of the BAU peak heating load (Table 6.32), the resulting heat load is roughly 2.9 MMBtu/hr for all nodes. For phase 1b, the geothermal field size decreases to around 75 feet long by 75 feet wide, resulting in an installation area of over 5,600 square feet.

To provide for around 50% of phase 1b annual peak heating load with geothermal resources, 25 wellbores drilled to a depth of 450 m each, and two 70-ton heat pumps would provide for over 1.3 MMBtu/hr (47% of phase 1b heat load). The remainder load of 1.5 MMBtu/hr (53% of phase 1b heat load) would be supplied by the natural gas peak boiler.

A pipe size of DN200 results in a pressure loss of around 97 Pa/m. If future district heating network expansion were considered prior to installation, selecting a larger pipe size (DN250) would also be appropriate for this case study. The heat loss of pipe size DN200 for insulation series 1, 2, and 3 is around 4.5 W/m, 3.7 W/m, and 3.1 W/m, respectively. The total capital cost for DN200 with insulation series 1, 2, and 3 for the total pipeline distribution length (>1,200 feet) is around $57,000, $67,000, and $76,000, respectively. For phase 1b of case study A, insulation series 3 for pipe size DN200 was selected to minimize heat loss in the distribution pipes.

For the large commercial building, the WSGHP system was sized to cover over 82% of the estimated annual peak heating load. With energy conservation measures considered in phase 1b, the heat load for the large commercial building drops to around 1.2 MMBtu/hr, requiring at least two 50-ton heat pumps (1 heat pump unit less than BAU scenario). For the mid-sized commercial building, the heat load is over 760,000 Btu/hr, requiring at least three 28-ton heat pumps to cover over 85% of peak demand. For the small commercial building, two 5-ton heat pumps cover roughly 93% of the heat load. For residential buildings with annual peak heating loads of around 75,000 Btu/hr each, three 3-ton heat pumps cover over 110% of the load.

The Model Output for phase 1b of case study A is provided in tables 6.38 – 6.40. From Table 6.38, the CAP and LOM costs, and TCO for the geothermal system is around $0.4 million dollars, \$0.5 million dollars, and \$0.9 million dollars, respectively. For the supplementary natural gas peak boiler, the CAP and LOM costs, and TCO are over \$53,000, \$139,000, and \$0.2 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating boiler throughout the lifetime of the GSDE network is around \$1.1 million dollars.

Table 6.38 – Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 1b of case study A. The Energy Production System covers around 47% of phase 1b peak heating load from geothermal resources and 53% of phase 1b peak heating load from a supplementary natural gas boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD(S) COSTS						
Capital Costs ($MM) (with incentives)	0.4	0.0	0.0	0.0	0.0	0.4
Lifetime Operating and Maintenance Costs (20 years) ($MM)	0.5	0.0	0.0	0.0	0.0	0.5
Geothermal Total Cost of Ownership (20 years) ($MM)	0.9	0.0	0.0	0.0	0.0	0.9
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						53,706
Lifetime Operating and Maintenance Costs (20 years) ($)						139,188
Boiler Total Cost of Ownership (20 years) ($MM)						0.2
Total Energy Production System Cost (20 years) ($MM)						**1.1**

In Table 6.39, the CAP costs, TCO, AECS, and PB for the Energy Consumption System is provided. For the large commercial building, the CAP cost and TCO is around \$180,000 and over \$590,000, respectively. The AECS per year and PB for the large commercial building is over \$43,000 per year and 4 years, respectively.

For the mid-size commercial building, the CAP cost and TCO is over $150,000 and over $460,000, respectively. The AECS per year and PB is over $23,000 per year and 6 years, respectively. For the small commercial building, the CAP cost and TCO is around $18,000 and over $65,000, respectively. The AECS per year and PB is over $3,300 per year and 5 years, respectively. The CAP cost and TCO for each residential building is over $12,000 and over $63,000, respectively. For each residential building, the AECS per year and PB is over $1,700 per year and 7 years, respectively.

Table 6.39 – Energy Consumption System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), total cost of ownership (TCO), total annual energy cost savings per year (AECS), and payback period (PB) for phase 1b of case study A.

D. ENERGY CONSUMPTION SYSTEM - Model Output							
Energy Consumption System Analysis - Summary of Consumers Cost							
Total Cost of Ownership for Consumers ($M) and Payback Period (years)							
Nodes	Description	No. of Units	Total Node Capital Cost (with incentives) ($)	Total Node Lifetime (20 years) Operating and Maintenance Costs ($)	Total Node Lifetime (20 years) Cost of Ownership ($)	Total Node Annual Energy Cost Savings ($/year)	Payback Period (years) Per Unit
Node 1	Commercial (Large)	1	180,000	418,388	598,388	43,244	4
Node 2	Commercial (Mid)	1	151,200	313,260	464,460	23,284	6
Node 3	Commercial (Small)	1	18,000	47,538	65,538	3,307	5
Node 4	Residential	10	126,000	512,405	638,405	17,673	7

From Table 6.40, the CAP and LOM costs, and TCO for the GSDE network is $1.0 million dollars, $2.0 million dollars, and $3.1 million dollars, respectively. The AECS for all of the consumers connected to the GSDE network is around $0.1 million dollars per year, and the PB for the entire network is around 12 years. The total lifetime annual energy produced is over 374,000 MMBtu resulting in a LCOH of $8.2/MMBtu. The PB and LCOH for phase 1b of case study A also indicate that a GSDE network within the study area is techno-economically feasible.

Table 6.40 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 1b of case study A.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	1.1
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.1
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	1.8
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	3.1
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	0.5
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.5
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.0
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	12
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	0.7
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	380
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN200; Series 3 ($/m)	188
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.3
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.0
Total Lifetime Annual Energy Produced (MMBtu)	374461
Levelized Cost of Heat ($/MMBtu)	8.2

Phase 2: 50% Reduction in BAU Peak Heating Load + Additional Energy Nodes

For phase 2, a 50% reduction in the BAU annual peak heating load and the addition of adjacent energy nodes are considered for the study area. From Table 6.33, 9 energy nodes with 28 individual units have a total estimated heating load of over 2.7 MMBtu/hr.

The geothermal field size that provides around 50% of the heat load for phase 2 is roughly 75 feet long by 75 feet wide, resulting in an installation area of over 5,600 square feet. From the energy conservation measures considered in phase 2, the addition of adjacent nodes to the energy network does not significantly affect the design of the GSDE network when compared to phases 1a and 1b. Approximately 25 wellbores, each drilled to a depth of 450 m, and two 70-ton heat pumps would provide for over 1.3 MMBtu/hr (49% of phase 2 heat load).

The remainder load of 1.4 MMBtu/hr (51% of phase 2 heat load) would be supplied by the natural gas peak boiler.

A pipe size of DN200 results in a pressure loss of around 88 Pa/m. The heat loss of pipe size DN200 for insulation series 1, 2, and 3 is around 4.5 W/m, 3.7 W/m, and 3.1 W/m, respectively. The total capital cost of insulation series 1, 2, and 3 for the total pipeline distribution length (>2,000 feet) is around $90,000, $110,000, and $120,000, respectively. For phase 2 of case study A, insulation series 3 for pipe size DN200 was selected.

For the large commercial building, WSGHPs were sized to cover around 80% of the estimated annual peak heat load of the building. With energy conservation measures of 50% from BAU scenario, the heat load for the large commercial building drops to roughly 830,000 MMBtu/hr, requiring at least one 70-ton heat pump. For the mid-sized commercial building, the heat load is over 510,000 Btu/hr, requiring at least two 28-ton heat pumps to cover over 85% of peak demand. For each small commercial building, two 3-ton heat pumps cover over 75% of the building’s heat load. For each residential building with annual peak heat load of around 50,000 Btu/hr, two 3-ton heat pumps cover over 110% of the load.

The Model Output for phase 2 of case study A is provided in tables 6.41 – 6.43. From Table 6.41, the CAP and LOM costs, and TCO for the geothermal system is around $0.4 million dollars, $0.5 million dollars, and $0.9 million dollars, respectively. For the supplementary natural gas peak boiler, the CAP and LOM costs, and TCO are over $48,000, $126,000, and $0.2 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating boiler throughout the lifetime of the GSDE network is around $1.1 million dollars.

Table 6.41 – Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 2 of case study A. The Energy Production System covers around 49% of phase 2 heat load from geothermal resources and 51% of phase 2 heat load from a supplementary natural gas boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	0.4	0.0	0.0	0.0	0.0	0.4
Lifetime Operating and Maintenance Costs (20 years) ($MM)	0.5	0.0	0.0	0.0	0.0	0.5
Geothermal Total Cost of Ownership (20 years) ($MM)	0.9	0.0	0.0	0.0	0.0	0.9
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						48,692
Lifetime Operating and Maintenance Costs (20 years) ($)						126,194
Boiler Total Cost of Ownership (20 years) ($MM)						0.2
Total Energy Production System Cost (20 years) ($MM)						1.1

In Table 6.42, the CAP costs, TCO, AECS, and PB for the Energy Consumption System is provided. For the large commercial building, the CAP cost and TCO is over $125,000 and over $389,000, respectively. The AECS per year and PB for the large commercial building is over $29,000 per year and 4 years, respectively.

For the mid-size commercial building, the CAP cost and TCO is over $100,000 and over $300,000, respectively. The AECS per year and PB is over $15,000 per year and 6 years, respectively. For each small commercial buildings, the CAP cost and TCO is over $10,000 and over $39,000, respectively. The AECS per year and PB is over $2,500 per year and 4 years, respectively. The CAP cost and TCO for each residential building is over $8,000 and over

$42,000, respectively. For each residential building, the AECS per year and PB is around $1,200 per year and 7 years, respectively.

Table 6.42 – Energy Consumption System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), total cost of ownership (TCO), total annual energy cost savings per year (AECS), and payback period (PB) for phase 2 of case study A.

D. ENERGY CONSUMPTION SYSTEM - Model Output							
Energy Consumption System Analysis - Summary of Consumers Cost							
Total Cost of Ownership for Consumers ($M) and Payback Period (years)							
Nodes	Description	No. of Units	Total Node Capital Cost (with incentives) ($)	Total Node Lifetime (20 years) Operating and Maintenance Costs ($)	Total Node Lifetime (20 years) Cost of Ownership ($)	Total Node Annual Energy Cost Savings ($/year)	Payback Period (years) Per Unit
Node 1	Commercial (Large)	1	126,000	263,104	389,104	29,826	4
Node 2	Commercial (Mid)	1	100,800	208,840	309,640	15,523	6
Node 3	Commercial (Small)	1	10,800	28,287	39,087	2,567	4
Node 4	Residential	10	84,000	341,603	425,603	11,782	7
Node 5	Residential	5	42,000	170,802	212,802	5,891	7
Node 6	Residential	4	33,600	136,641	170,241	4,713	7
Node 7	Residential	3	25,200	102,481	127,681	3,535	7
Node 8	Commercial (Small)	2	21,600	56,573	78,173	5,134	4
Node 9	Commercial (Small)	1	10,800	28,287	39,087	2,567	4

From Table 6.43, the CAP and LOM costs, and TCO for the GSDE network is $1.0 million dollars, $2.1 million dollars, and $3.1 million dollars, respectively. The AECS for all of the consumers connected to the GSDE network is around $0.1 million dollars per year, and the PB for the entire network is around 13 years. The total lifetime annual energy produced is over 355,000 MMBtu resulting in a LCOH of $8.8/MMBtu. In phase 2 of case study A, a GSDE network also results in a feasible PB and LCOH for the study area described in Figure 6.6.

Table 6.43 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 2 of case study A.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	1.1
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	1.8
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	3.1
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	0.5
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.5
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.0
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	13
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	0.7
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	616
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN200; Series 3 ($/m)	170
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.3
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.1
Total Lifetime Annual Energy Produced (MMBtu)	355792
Levelized Cost of Heat ($/MMBtu)	8.8

Phase 3: 50% Reduction in BAU Peak Heating Load + Multiple Energy Nodes

In phase 3, multiple energy nodes extending to areas outside of the original study area are considered. The individual buildings are assumed to have 50% reductions in the annual peak heating load from the BAU case (Table 6.34). In phase 3, a total of 21 energy nodes with 63 individual units have a total estimated heat load of over 6 MMBtu/hr.

To provide around 56% of phase 3 annual peak heating load (~3.3 MMBtu/hr) with geothermal resources, at least two geothermal fields are required. For lot A, the geothermal field size is at least 105 feet long by 105 feet wide resulting in an installation area of over 11,000 square feet. For lot B, the field size is around 75 feet long by 75 feet wide resulting in an installation area of over 5,600 square feet.

Geothermal lot A requires a minimum of 49 wellbores, each drilled to a depth of 450 m, and three 70-ton heat pumps to provide for over 2.0 MMBtu/hr (33% of phase 3 heat load). Lot B requires a minimum of 25 wellbores, each drilled to a depth of 450 m, and two 70-ton heat pumps to provide for over 1.3 Btu/hr (22% of phase 3 heat load). The remainder load of 2.7 MMBtu/hr (44% of phase 3 heat load) would be supplied by the natural gas peak boiler.

From the GeoDistrict model, a pipe size of DN300 results in a pressure loss of around 53 Pa/m. The heat loss of pipe size DN300 for insulation series 1, 2, and 3 is around 5.2 W/m, 4.2 W/m, and 3.5 W/m, respectively. The total capital cost of insulation series 1, 2, and 3 for the total pipeline distribution length (>5,500 feet) is around \$410,000, \$480,000, and \$540,000, respectively. To ensure minimal heat loss for all the energy nodes in phase 3 of case study A, insulation series 3 for pipe size DN300 was selected.

For the large commercial building, the WSGHP requires at least one 70-ton heat pump unit to cover over 80% of its annual peak heat load demand of over 830,000 MMBtu/hr. For each mid-sized commercial building, at least two 28-ton heat pumps cover over 85% of peak demand of around 512,000 Btu/hr. For each small commercial buildings, at least two 3-ton heat pumps cover around 75% of the heat load. For each residential building, at least two 3-ton heat pumps cover over 110% of the load.

The Model Output for phase 3 of case study A is provided in tables 6.44 – 6.46. From Table 6.44, the CAP and LOM costs, and TCO for the geothermal system is around \$1.1 million dollars, \$1.3 million dollars, and \$2.4 million dollars, respectively. For the supplementary natural gas peak boiler the CAP and LOM costs, and TCO are over \$93,000, \$242,000, and \$0.3 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating boiler throughout the lifetime of the GSDE network is around $2.8 million dollars.

Table 6.44 – Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 3 of case study A. The Energy Production System covers around 56% of phase 3 annual peak load from geothermal resources and 44% of phase 3 annual peak load from a supplementary natural gas boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	0.7	0.4	0.0	0.0	0.0	1.1
Lifetime Operating and Maintenance Costs (20 years) ($MM)	0.8	0.5	0.0	0.0	0.0	1.3
Geothermal Total Cost of Ownership (20 years) ($MM)	1.5	0.9	0.0	0.0	0.0	2.4
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						93,485
Lifetime Operating and Maintenance Costs (20 years) ($)						242,284
Boiler Total Cost of Ownership (20 years) ($MM)						0.3
Total Energy Production System Cost (20 years) ($MM)						2.8

In Table 6.45, the CAP costs, TCO, AECS, and PB for the Energy Consumption System is provided. For the large commercial building, the CAP cost and TCO is around $126,000 and over $389,000, respectively. The AECS per year and PB for the large commercial building is over $29,000 per year and 4 years, respectively.

For each mid-size commercial building, the CAP cost and TCO is over $100,000 and over $300,000, respectively. The AECS per year and PB is over $15,000 per year and 6 years, respectively. For each small commercial building, the CAP cost and TCO is over $10,000 and over $39,000, respectively. The AECS per year and PB is over $2,500 per year and 4 years, respectively. For each residential building, the CAP cost and TCO is over $8,000 and over $42,000, respectively. The AECS per year and PB is around $1,200 per year and 7 years, respectively.

Table 6.45 - Energy Consumption System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), total cost of ownership (TCO), total annual energy cost savings per year (AECS), and payback period (PB) for phase 3 of case study A.

D. ENERGY CONSUMPTION SYSTEM - Model Output							
Energy Consumption System Analysis - Summary of Consumers Cost							
Total Cost of Ownership for Consumers ($M) and Payback Period (years)							
Nodes	Description	No. of Units	Total Node Capital Cost (with incentives) ($)	Total Node Lifetime (20 years) Operating and Maintenance Costs ($)	Total Node Lifetime (20 years) Cost of Ownership ($)	Total Node Annual Energy Cost Savings ($/year)	Payback Period (years) Per Unit
Node 1	Commercial (Large)	1	126,000	263,104	389,104	29,826	4
Node 2	Commercial (Mid)	1	100,800	208,840	309,640	15,523	6
Node 3	Commercial (Small)	1	10,800	28,287	39,087	2,567	4
Node 4	Residential	10	84,000	341,603	425,603	11,782	7
Node 5	Residential	2	16,800	68,321	85,121	2,356	7
Node 6	Residential	4	33,600	136,641	170,241	4,713	7
Node 7	Residential	5	42,000	170,802	212,802	5,891	7
Node 8	Residential	3	25,200	102,481	127,681	3,535	7
Node 9	Commercial (Small)	2	21,600	56,573	78,173	5,134	4
Node 10	Commercial (Small)	1	10,800	28,287	39,087	2,567	4
Node 11	Commercial (Small)	1	10,800	28,287	39,087	2,567	4
Node 12	Commercial (Small)	2	21,600	56,573	78,173	5,134	4
Node 13	Commercial (Mid)	2	201,600	417,680	619,280	31,046	6
Node 14	Commercial (Small)	2	21,600	56,573	78,173	5,134	4
Node 15	Commercial (Small)	1	10,800	28,287	39,087	2,567	4
Node 16	Commercial (Small)	1	10,800	28,287	39,087	2,567	4
Node 17	Residential	2	16,800	68,321	85,121	2,356	7
Node 18	Commercial (Mid)	1	100,800	208,840	309,640	15,523	6
Node 19	Residential	7	58,800	239,122	297,922	8,248	7
Node 20	Residential	8	67,200	273,282	340,482	9,426	7
Node 21	Residential	6	50,400	204,962	255,362	7,069	7
Total for All Consumers ($MM)			1.04	3.02	4.06	0.18	

From Table 6.46, the CAP and LOM costs, and TCO for the entire GSDE network is $2.8 million dollars, $5 million dollars, and $7.8 million dollars, respectively. The AECS for all consumers connected to the GSDE network is around $0.2 million dollars per year, and the PB for the entire network is roughly 16 years. The total lifetime annual energy produced is over 784,000 MMBtu resulting in a LCOH of $10.0/MMBtu. In phase 3 of case study A, a GSDE network also results in a feasible PB and LCOH for the study area described in Figure 6.6.

Table 6.46 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 3 of case study A.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	2.8
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN300; Series 3	1.0
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	4.1
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	7.8
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	1.2
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN300; Series 3	0.5
Total Node Capital Costs (All Consumers) ($MM)	1.0
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	2.8
All Consumers Annual Energy Costs Savings ($MM/year)	0.2
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	16
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	1.6
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	1699
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN300; Series 3 ($/m)	257
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.4
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	3.0
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	5.0
Total Lifetime Annual Energy Produced (MMBtu)	784306
Levelized Cost of Heat ($/MMBtu)	10.0

6.4.2: Case Study B: Geothermal Resources Providing Around 70% of Annual Peak Heating Load

Phase 1a: Business-as-Usual (BAU) Peak Heating Load

To provide around 70% of the BAU annual peak heating load with geothermal resources, a field size of at least 135 feet long by 135 feet wide is required resulting in an installation area of over 18,000 square feet. A geothermal field of at least 80 wellbores, each drilled to a depth of 450 m, and four 70-ton heat pumps would provide over 2.6 MMBtu/hr (70% of phase 1a heat load). The remainder load of 1.2 MMBtu/hr (30% of phase 1a heat load) can be supplied with the natural gas peak boiler.

In both case studies A and B, building heat load and distribution distances for all energy phases follow tables 6.31 – 6.34 described in Section 6.4. In addition, the total energy produced by the geothermal fields and natural gas peak boiler for all phases of case studies A and B provide for exactly 100% of the area's total annual peak heating load. Similar to phase 1a of case study A, the pipe size and insulation series in the Energy Distribution System for phase 1a of case study B involves pipe size DN250 with insulation series 3.

The Model Output for the Energy Production System and GSDE network for phase 1a of case study B is provided in tables 6.47 – 6.48, respectively. The Energy Consumption System Model Output for phase 1a of case study B follows Table 6.36 in Section 6.4.1. From Table 6.47, the CAP and LOM costs, and TCO for the geothermal system that provides approximately 70% of phase 1a annual peak heating load is around \$1.0 million dollars, \$1.1 million dollars, and \$2.1 million dollars, respectively. For the natural gas peak boiler providing for the remainder 30% heat load, the CAP and LOM costs, and TCO are over \$40,000, \$100,000, and \$0.1 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating boiler throughout the lifetime of the GSDE network is around $2.2 million dollars.

Table 6.47 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 1a of case study B. The Energy Production System covers around 70% of the area's heat load from geothermal resources and 30% of the heat load from a supplementary natural gas boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	1.0	0.0	0.0	0.0	0.0	1.0
Lifetime Operating and Maintenance Costs (20 years) ($MM)	1.1	0.0	0.0	0.0	0.0	1.1
Geothermal Total Cost of Ownership (20 years) ($MM)	2.1	0.0	0.0	0.0	0.0	2.1
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						40,369
Lifetime Operating and Maintenance Costs (20 years) ($)						104,624
Boiler Total Cost of Ownership (20 years) ($MM)						0.1
Total Energy Production System Cost (20 years) ($MM)						**2.2**

From Table 6.48, the CAP and LOM costs, and TCO for the GSDE network is $1.8 million dollars, $3 million dollars, and $4.9 million dollars, respectively. The AECS for all consumers connected to the GSDE network is around $0.1 million dollars per year, and the PB for the entire network is roughly 17 years. The total lifetime annual energy produced is over 499,000 MMBtu resulting in a LCOH of $9.8/MMBtu, which is a competitive LCOH for low-grade geothermal applications (Beckers, 2016).

Table 6.48 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 1a of case study B.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	2.2
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	2.5
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	4.9
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	1.1
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.7
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.8
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	17
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	1.2
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	380
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN250; Series 3 ($/m)	190
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.8
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	3.0
Total Lifetime Annual Energy Produced (MMBtu)	499282
Levelized Cost of Heat ($/MMBtu)	9.8

Phase 1b: 25% Reduction in BAU Peak Heating Load

For phase 1b of case study B, to provide for 70% of the area's annual peak heating load with geothermal resources, a field size of 105 feet long by 105 feet wide is required resulting in an installation area of over 11,000 square feet. Approximately, 50 geothermal wellbores, each drilled to a depth of 450 m, and three 70-ton heat pumps would provide for over 2.0 MMBtu/hr (70% of phase 1b heat load). The remainder load of 0.9 MMBtu/hr (30% of phase 1b heat load) can be supplied with the natural gas peak boiler.

The Model Output of the Energy Production System cost and GSDE network costs for phase 1b of case study B is provided in tables 6.49 – 6.50, respectively. For the Energy Consumption System for phase 1b of case study B, the Model Output follows Table 6.39 in

Section 6.4.1. The pipe size and insulation series in the Energy Distribution System for phase 1b of case study B involves pipe size DN200 with insulation series 3.

For phase 1b of case study B, the CAP and LOM costs, and TCO for the geothermal system that provides approximately 70% of phase 1b annual peak heating load is around \$0.7 million dollars, \$0.8 million dollars, and \$1.5 million dollars, respectively (see Table 6.49). For the natural gas peak boiler providing for the remainder 30% heat load, the CAP and LOM costs, and TCO are over \$30,000, \$78,000, and \$0.1 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating boiler throughout the lifetime of the GSDE network is around \$1.6 million dollars.

Table 6.49 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 1b of case study B. The Energy Production System covers around 70% of phase 1b heat load from geothermal resources and 30% of phase 1b heat load from a supplementary natural gas boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	0.7	0.0	0.0	0.0	0.0	0.7
Lifetime Operating and Maintenance Costs (20 years) ($MM)	0.8	0.0	0.0	0.0	0.0	0.8
Geothermal Total Cost of Ownership (20 years) ($MM)	1.5	0.0	0.0	0.0	0.0	1.5
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						30,277
Lifetime Operating and Maintenance Costs (20 years) ($)						78,468
Boiler Total Cost of Ownership (20 years) ($MM)						0.1
Total Energy Production System Cost (20 years) ($MM)						1.6

From Table 6.50, the CAP and LOM costs, and TCO for the GSDE network is $1.3 million dollars, $2.2 million dollars, and $3.5 million dollars, respectively. The AECS for all consumers connected to the GSDE network is around $0.1 million dollars per year, and the PB for the entire network is roughly 15 years. The total lifetime annual energy produced is over 374,000 MMBtu resulting in a LCOH of $9.4/MMBtu.

Table 6.50 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the entire geothermal district energy (GSDE) network for phase 1b of case study B.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	1.6
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.1
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	1.8
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	3.5
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	0.7
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.5
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.3
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	15
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	0.9
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	380
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN200; Series 3 ($/m)	188
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.3
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.2
Total Lifetime Annual Energy Produced (MMBtu)	374461
Levelized Cost of Heat ($/MMBtu)	9.4

Phase 2: 50% Reduction in BAU Peak Heating Load + Additional Energy Nodes

For phase 2 of case study B, to provide for around 70% of the area's annual peak heating load with geothermal resources, a field size of 105 feet long by 105 feet wide is required resulting in an installation area of over 11,000 square feet. Approximately 50 geothermal wellbores drilled to a depth of 450 m each, and three 70-ton heat pumps provide for over 2.0

MMBtu/hr (74% of phase 2 heat load). The remainder load of 0.7 MMBtu/hr (26% of phase 2 heat load) can be supplied with the natural gas peak boiler.

The Model Output of the Energy Production System cost and GSDE network costs for phase 2 of case study B is provided in tables 6.51 – 6.52, respectively. For the Energy Consumption System for phase 2 of case study B, the Model Output follows Table 6.42 in Section 6.4.1. The pipe size and insulation series in the Energy Distribution System for phase 2 of case study B involves pipe size DN200 with insulation series 3.

The CAP and LOM costs, and TCO for the geothermal system that provides approximately 74% of phase 2 annual peak heating load is around $0.7 million dollars, $0.8 million dollars, and $1.5 million dollars, respectively (see Table 6.51). For the natural gas peak boiler providing for the remainder 26% heat load, the CAP and LOM costs, and TCO are over $25,000, $65,000, and $0.1 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating boiler throughout the lifetime of the GSDE network is around $1.6 million dollars.

Table 6.51 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 2 of case study B. The Energy Production System covers around 74% of phase 2 heat load from geothermal resources and 26% of phase 2 heat load from a supplementary natural gas boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	0.7	0.0	0.0	0.0	0.0	0.7
Lifetime Operating and Maintenance Costs (20 years) ($MM)	0.8	0.0	0.0	0.0	0.0	0.8
Geothermal Total Cost of Ownership (20 years) ($MM)	1.5	0.0	0.0	0.0	0.0	1.5
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						25,263
Lifetime Operating and Maintenance Costs (20 years) ($)						65,474
Boiler Total Cost of Ownership (20 years) ($MM)						0.1
Total Energy Production System Cost (20 years) ($MM)						**1.6**

From Table 6.52, the CAP and LOM costs, and TCO for the GSDE network is \$1.3 million dollars, \$2.3 million dollars, and \$3.7 million dollars, respectively. The AECS for all consumers connected to the GSDE network is around \$0.1 million dollars per year, and the PB for the entire network is roughly 17 years. The total lifetime annual energy produced is over 355,000 MMBtu resulting in a LCOH of \$10.3/MMBtu.

Table 6.52 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 2 of case study B.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	1.6
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	1.9
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	3.7
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	0.7
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN200; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.5
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.3
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	17
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	0.9
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	616
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN200; Series 3 ($/m)	170
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.4
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.3
Total Lifetime Annual Energy Produced (MMBtu)	355792
Levelized Cost of Heat ($/MMBtu)	10.3

Phase 3: 50% Reduction in BAU Peak Heating Load + Multiple Energy Nodes

For phase 3 of case study B, to provide around 70% of the area's peak heating load with geothermal resources, at least two geothermal fields are required. For lot A, the geothermal field size is at least 135 feet long by 135 feet wide, resulting in an installation area of over 18,000 square feet. For lot B, the field size is around 105 feet long by 105 feet wide, resulting in an installation area of over 11,000 square feet.

Geothermal lot A requires over 80 wellbores, each drilled to a depth of 450 m, and four 70-ton heat pumps to provide for over 2.6 MMBtu/hr (45% of phase 3 heat load). Lot B requires almost 50 wellbores, each drilled to a depth of 450 m, and three 70-ton heat pumps to provide for over 2.0 MMBtu/hr (33% of phase 3 heat load). The remainder load of 1.3 MMBtu/hr (22% of phase 3 heat load) would be supplied by the natural gas peak boiler.

The Model Output of the Energy Production System cost and GSDE network costs for phase 3 of case study B is provided in tables 6.53 – 6.54, respectively. For the Energy Consumption System for phase 3 of case study B, the Model Output follows Table 6.45 in Section 6.4.1. The pipe size and insulation series in the Energy Distribution System for phase 3 of case study B involves pipe size DN300 with insulation series 3.

From Table 6.53, the CAP and LOM costs, and TCO for the geothermal system that provides approximately 78% of phase 3 annual peak load is around $1.7 million dollars, $1.8 million dollars, and $3.6 million dollars, respectively. For the natural gas peak boiler providing for the remainder 22% of phase 3 heat load, the CAP and LOM costs, and TCO are over $46,000, $120,000, and $0.2 million dollars, respectively. The total energy production cost for both the geothermal system and supplementary heating boiler throughout the lifetime of the GSDE network is around $3.7 million dollars.

From Table 6.54, the CAP and LOM costs, and TCO for the GSDE network is $3.4 million dollars, $5.4 million dollars, and $8.8 million dollars, respectively. The AECS for all consumers connected to the geothermal district network is around $0.2 million dollars per year, and the PB for the entire network is roughly 19 years. The total lifetime annual energy produced is over 784,000 MMBtu resulting in a LCOH of $11.2/MMBtu.

Table 6.53 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 3 of case study B. The Energy Production System covers around 78% of phase 3 heat load from geothermal resources and 22% of phase 3 heat load from a supplementary natural gas boiler.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	1.0	0.7	0.0	0.0	0.0	1.7
Lifetime Operating and Maintenance Costs (20 years) ($MM)	1.1	0.8	0.0	0.0	0.0	1.8
Geothermal Total Cost of Ownership (20 years) ($MM)	2.1	1.5	0.0	0.0	0.0	3.6
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						46,627
Lifetime Operating and Maintenance Costs (20 years) ($)						120,842
Boiler Total Cost of Ownership (20 years) ($MM)						0.2
					Total Energy Production System Cost (20 years) ($MM)	**3.7**

Table 6.54 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the entire geothermal district heating and cooling network for phase 3 of case study B.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	3.7
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN300; Series 3	1.0
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	4.1
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	8.8
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	1.8
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN300; Series 3	0.5
Total Node Capital Costs (All Consumers) ($MM)	1.0
Total Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	3.4
All Consumers Annual Energy Costs Savings ($MM/year)	0.2
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	19
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	2.0
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	1699.0
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN300; Series 3 ($/m)	256.5
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.4
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	3.0
Sum of the GeoDistrict Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	5.4
Total Lifetime Annual Energy Produced (MMBtu)	784306
Levelized Cost of Heat ($/MMBtu)	11.2

6.4.3: Case Study C: Geothermal Resources Providing Around 100% of Annual Peak Heating Load

Phase 1a: Business-as-Usual (BAU) Peak Heating Load

The design of a geothermal system that provides around 100% of the annual BAU peak heating load requires a field size approximately 180 feet long by 175 feet wide, resulting in an installation area of over 31,000 square feet. In the geothermal field, around 130 wellbores drilled to a depth of 450 m each, and six 70-ton heat pumps will provide over 4.0 MMBtu/hr, resulting in a slightly oversized geothermal system (105% of phase 1a heat load). For all energy phases of case study C, the geothermal system was slightly oversized because no supplemental natural gas peak boiler is considered.

Building heat load and distribution distances for all energy phases of case study C follow tables 6.31 – 6.34 described in Section 6.4. From the Energy Distribution System, a pipe size of DN250 results in a pressure loss of 61 Pa/m of pipe installed, which ensures an adequate pressure drop of 50 – 100 Pa/m. For phase 1a of case study C, an adequate pipe size and insulation series is pipe size DN250 with insulation series 3.

The Model Output of the Energy Production System and GSDE network costs for phase 1a of case study C is provided in tables 6.55 – 6.56, respectively. The Energy Consumption System Model Output for phase 1a of case study C follows Table 6.36 in Section 6.4.1 because individual building heat load and distribution distances remained unchanged for case study C. For the geothermal system that provides approximately 105% of the BAU annual peak heating load, the CAP and LOM costs are around $1.6 million dollars each, and the TCO is around $3.2 million dollars (see Table 6.55).

Table 6.55 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 1a of case study C. The Energy Production System covers around 105% of the annual peak heating load from geothermal resources.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	1.6	0.0	0.0	0.0	0.0	1.6
Lifetime Operating and Maintenance Costs (20 years) ($MM)	1.6	0.0	0.0	0.0	0.0	1.6
Geothermal Total Cost of Ownership (20 years) ($MM)	3.2	0.0	0.0	0.0	0.0	3.2
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						-
Lifetime Operating and Maintenance Costs (20 years) ($)						-
Boiler Total Cost of Ownership (20 years) ($MM)						0.0
Total Energy Production System Cost (20 years) ($MM)						**3.2**

From Table 6.56, the CAP and LOM costs, and TCO for the GSDE network is $2.4 million dollars, $3.5 million dollars, and $5.8 million dollars, respectively. The energy cost savings for all consumers connected to the GSDE network is over $0.1 million dollars per year, and the PB for the entire network is over 21 years. The PB for phase 1a of case study C is greater than the estimated lifetime of the GSDE network (20 years). The total lifetime annual energy produced is over 523,000 MMBtu resulting in a LCOH of $11.2/MMBtu.

Table 6.56 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 1a of case study C.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	3.2
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	2.5
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	5.8
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	1.6
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.7
Sum of the Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	2.4
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	21
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	1.6
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	380
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN250; Series 3 ($/m)	205
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.8
Sum of Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	3.5
Total Lifetime Annual Energy Produced (MMBtu)	523444
Levelized Cost of Heat ($/MMBtu)	11.2

Phase 1b: 25% Reduction in BAU Peak Heating Load

For phase 1b of case study C, the geothermal system requires an installation area of over 22,000 square feet based on a field size of 150 feet long by 150 feet wide. Approximately 100 geothermal wellbores drilled to a depth of 450 m each, and five 70-ton heat pumps provide for over 3.3 MMBtu/hr (116% of phase 1b peak load). From the Energy Distribution System, an adequate pipe size and insulation series for phase 1b of case study C is pipe size DN250 with insulation series 3.

The Model Output of the Energy Production System and GSDE network costs for phase 1b of case study C is provided in tables 6.57 – 6.58, respectively. The Energy Consumption

System Model Output for phase 1b of case study C follows Table 6.39 in Section 6.4.1 because individual building heat load and distribution distances remained unchanged for case study C.

From Table 6.57, the CAP and LOM costs for the geothermal system that provides over 115% of the annual peak heating load is around $1.3 million dollars each, and the TCO is around $2.6 million dollars. From Table 6.58, the CAP and LOM costs, and TCO for the GSDE network is $1.9 million dollars, $2.7 million dollars, and $4.5 million dollars, respectively. The PB for the entire network and LCOH is over 21 years and $10.4/MMBtu, respectively.

Table 6.57 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 1b of case study C. The Energy Production System covers over 115% of the annual peak heating load from geothermal resources.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	1.3	0.0	0.0	0.0	0.0	1.3
Lifetime Operating and Maintenance Costs (20 years) ($MM)	1.3	0.0	0.0	0.0	0.0	1.3
Geothermal Total Cost of Ownership (20 years) ($MM)	2.6	0.0	0.0	0.0	0.0	2.6
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						-
Lifetime Operating and Maintenance Costs (20 years) ($)						-
Boiler Total Cost of Ownership (20 years) ($MM)						0.0
Total Energy Production System Cost (20 years) ($MM)						2.6

Table 6.58 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 1b of case study C.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	2.6
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	1.8
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	4.5
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	1.3
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.1
Total Node Capital Costs (All Consumers) ($MM)	0.5
Sum of the Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.9
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	21
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	1.3
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	380
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN250; Series 3 ($/m)	155
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.3
Sum of Total Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.7
Total Lifetime Annual Energy Produced (MMBtu)	436203
Levelized Cost of Heat ($/MMBtu)	10.4

Phase 2: 50% Reduction in BAU Peak Heating Load + Additional Energy Nodes

For phase 2 of case study C, the reduction in annual peak heating load from energy conservation measures and the addition of adjacent energy nodes does not significantly affect the design of the geothermal system when compared to phase 1b. For phase 2, the geothermal system requires a field size approximately 150 feet long by 150 feet wide, resulting in an installation area of over 22,000 square feet. Around 100 geothermal wellbores drilled to a depth of 450 m each, and five 70-ton heat pumps will provide over 3.3 MMBtu/hr (123% of phase 2 heat load). From the Energy Distribution System, an adequate pipe size and insulation series for phase 2 of case study C is pipe size DN250 with insulation series 3.

The Model Output of the Energy Production System and GSDE network costs for phase 2 is provided in tables 6.59 – 6.60, respectively. The Energy Consumption System Model Output for phase 2 of case study C follows Table 6.42 in Section 6.4.1.

From Table 6.59, the CAP and LOM costs for the geothermal system that provides approximately 123% of the annual peak load is around \$1.3 million dollars each, and the TCO is around \$2.6 million dollars. From Table 6.60, the CAP cost, LOM costs, and TCO for the GSDE network is \$1.9 million dollars, \$2.8 million dollars, and \$4.7 million dollars, respectively. The PB for the entire network and LCOH is almost 25 years and \$10.8/MMBtu, respectively.

Table 6.59 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 2 of case study C. The Energy Production System covers around 123% of the peak load from geothermal resources.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	1.3	0.0	0.0	0.0	0.0	1.3
Lifetime Operating and Maintenance Costs (20 years) ($MM)	1.3	0.0	0.0	0.0	0.0	1.3
Geothermal Total Cost of Ownership (20 years) ($MM)	2.6	0.0	0.0	0.0	0.0	2.6
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						-
Lifetime Operating and Maintenance Costs (20 years) ($)						-
Boiler Total Cost of Ownership (20 years) ($MM)						0.00
Total Energy Production System Cost (20 years) ($MM)						2.6

Table 6.60 - Summary of the Total Energy Production, Distribution Network, and Consumption costs for the geothermal district energy (GSDE) network for phase 2 of case study C.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	2.6
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.3
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	1.9
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	4.7
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	1.3
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN250; Series 3	0.2
Total Node Capital Costs (All Consumers) ($MM)	0.5
Sum of the Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	1.9
All Consumers Annual Energy Costs Savings ($MM/year)	0.1
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	25
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	1.3
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	616
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN250; Series 3 ($/m)	155
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.1
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	1.4
Sum of the Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	2.8
Total Lifetime Annual Energy Produced (MMBtu)	436203
Levelized Cost of Heat ($/MMBtu)	10.8

Phase 3: 50% Reduction in BAU Peak Heating Load + Multiple Energy Nodes

For phase 3 of case study C, two geothermal fields are required to provide for over 120% of the annual peak heating load with geothermal resources. For Lot A, the geothermal field size is at least 175 feet long by 180 feet wide, resulting in an installation area of over 31,00 square feet. For Lot B, the field size is around 150 feet long by 150 feet wide, resulting in an installation area of over 22,000 square feet.

Geothermal lot A requires over 130 wellbores drilled to a depth of 450 m each, and six 70-ton heat pumps to provide for over 4.0 MMBtu/hr (67% of phase 3 heat load). Lot B requires around 100 wellbores, each drilled to a depth of 450 m, and five 70-ton heat pumps to provide for over 3.3 Btu/hr (56% of phase 3 heat load). In total, lots A and B provide over 7.3

MMBtu/hr, which is around 122% of the estimated annual peak heating load for phase 3 of case study C.

The Model Output of the Energy Production System cost and GSDE network costs for phase 3 of case study C is provided in tables 6.61 – 6.62, respectively. For the Energy Consumption System for phase 3 of case study C, the economic model output follows Table 6.45 in Section 6.4.1. The pipe size and insulation series in the Energy Distribution System for phase 3 of case study C involves pipe size DN300 with insulation series 3.

From Table 6.61, the CAP and LOM costs for the geothermal system that provides approximately 122% of the annual peak heating load is around $2.9 million dollars each, and the TCO is around $5.8 million dollars. From Table 6.62, the CAP and LOM costs, and TCO for the GSDE network is $4.5 million dollars, $6.6 million dollars, and $11 million dollars, respectively. The PB for the entire network and LCOH is roughly 26 years and $11.5/MMBtu, respectively.

Table 6.61 - Energy Production System summary of capital costs (CAP), lifetime operating and maintenance costs (LOM), and total cost of ownership (TCO) for phase 3 of case study C. The Energy Production System covers around 122% of the annual peak heating load from geothermal resources.

D. ENERGY PRODUCTION SYSTEM - Model Output						
Energy Production System Analysis - Summary of Energy Costs						
Total Cost of Ownership (20 years) for the Energy Production System						
	Geothermal LOT A	Geothermal LOT B	Geothermal LOT C	Geothermal LOT D	Geothermal LOT E	Total Cost ($)
GEOTHERMAL FIELD COSTS						
Capital Costs ($MM) (with incentives)	1.6	1.3	0.0	0.0	0.0	2.9
Lifetime Operating and Maintenance Costs (20 years) ($MM)	1.6	1.3	0.0	0.0	0.0	2.9
Geothermal Total Cost of Ownership (20 years) ($MM)	3.2	2.6	0.0	0.0	0.0	5.8
NATURAL GAS PEAK BOILER COSTS						
Capital Costs ($)						-
Lifetime Operating and Maintenance Costs (20 years) ($)						-
Boiler Total Cost of Ownership (20 years) ($MM)						0.0
Total Energy Production System Cost (20 years) ($MM)						5.8

Table 6.62 - Summary of the total energy production, distribution network, and consumption costs for the geothermal district energy (GSDE) network for phase 3 of case study C.

D. OVERALL GEOTHERMAL DISTRICT HEATING AND COOLING NETWORK - Model Output	
Summary of Total Energy Production, Distribution Network, and Consumers Costs	
Total Energy Production System Cost (20 years) ($MM)	5.8
Total Cost for Distribution Network by Insulation Series (20 years) ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN300; Series 3	1.2
Total Node Lifetime Cost for all Consumers (20 years) ($MM)	4.1
Sum of the Total Cost of Ownership for Energy Production, Distribution, and Consumption Systems ($MM)	11.0
Estimated Payback Period for Geothermal District Heating and Cooling Distribution Network	
Capital Cost Energy Production ($MM)	2.9
Capital Cost for Distribution Network by Insulation Series ($MM)	
Pipe Size (DN,mm) and Insulation Class: DN300; Series 3	0.5
Total Node Capital Costs (All Consumers) ($MM)	1.0
Sum of the Capital Cost for Energy Production, Distribution, and Consumption Systems ($MM)	4.5
All Consumers Annual Energy Costs Savings ($MM/year)	0.2
Payback Period for Geothermal District Heating and Cooling Distribution Network (years)	26
Standard Levelized Cost Model	
Total Lifetime Operation & Maintenance Energy Production System (20 years) ($MM)	2.9
Energy Distribution System (20 years) ($MM)	
Total Distribution Length (m)	1699
Total Present Value (20 years) for Pipe Size (DN,mm) and Insulation Series: DN300; Series 3 ($/m)	381
Total Lifetime Operation & Maintenance Energy Distribution System (20 years) ($MM)	0.6
Total Lifetime Operation & Maintenance Energy Consumption System (20 years) ($MM)	3.0
Sum of the Lifetime Operation & Maintenance for Energy Production, Distribution, and Consumptiuon (20 years) ($MM)	6.6
Total Lifetime Annual Energy Produced (MMBtu)	959647
Levelized Cost of Heat ($/MMBtu)	11.5

6.4.4: Economic Comparison for All Energy Phases of Case Studies A, B, and C

A comparison of the total cost of ownership (TCO), payback period (PB), and levelized cost of heat (LCOH) for all energy phases of case studies A, B, and C is provided in this section based on the techno-economic results described in sections 6.4 – 6.4.3. The objective of this section is to compare the economic feasibility of various GSDE network designs based on variations in building thermal energy demand, consumer distribution distances, and geothermal energy production.

In Figure 6.7, the TCO comparison of the GSDE network for all energy phases of case studies A, B, and C is provided. For all case studies, the TCO of phases 1b and 2 is the lowest suggesting that energy conservation measures that decrease annual peak heating load from BAU scenario result in lower capital, operating, and maintenance costs throughout the lifetime of the GSDE network. The TCO for phases 1b and 2 of case studies A, B, and C is in the range of \$3.1 million dollars - \$4.7 million dollars.

For all case studies, phase 3 results in the highest TCO because of the addition of more energy nodes to the original study area, which requires additional geothermal fields and longer distribution lines. The TCO for phase 3 of case studies A, B, and C is around \$7.8 million dollars, \$8.8 million dollars, and \$11.0 million dollars, respectively. Even though the TCO for phase 3 is higher than phases 1 and 2, more consumers benefit from the connection to the GSDE network. The capital, operating, and maintenance costs of the GSDE system may be spread among more consumers, increasing the attractiveness of larger GSDE installations.

As expected, case study A results in the lowest TCO for all energy phases, because only around 50% of the annual peak heating load is provided by geothermal resources. The remainder

50% peak load in case study A is provided by a supplemental natural gas peak boiler. Case study C results in the highest TCO for all energy phases, because the geothermal fields provide for all of the area's heat load and no supplemental natural gas peak boiler is considered. In addition, the geothermal fields are slightly overdesigned for some energy phases of case study C.

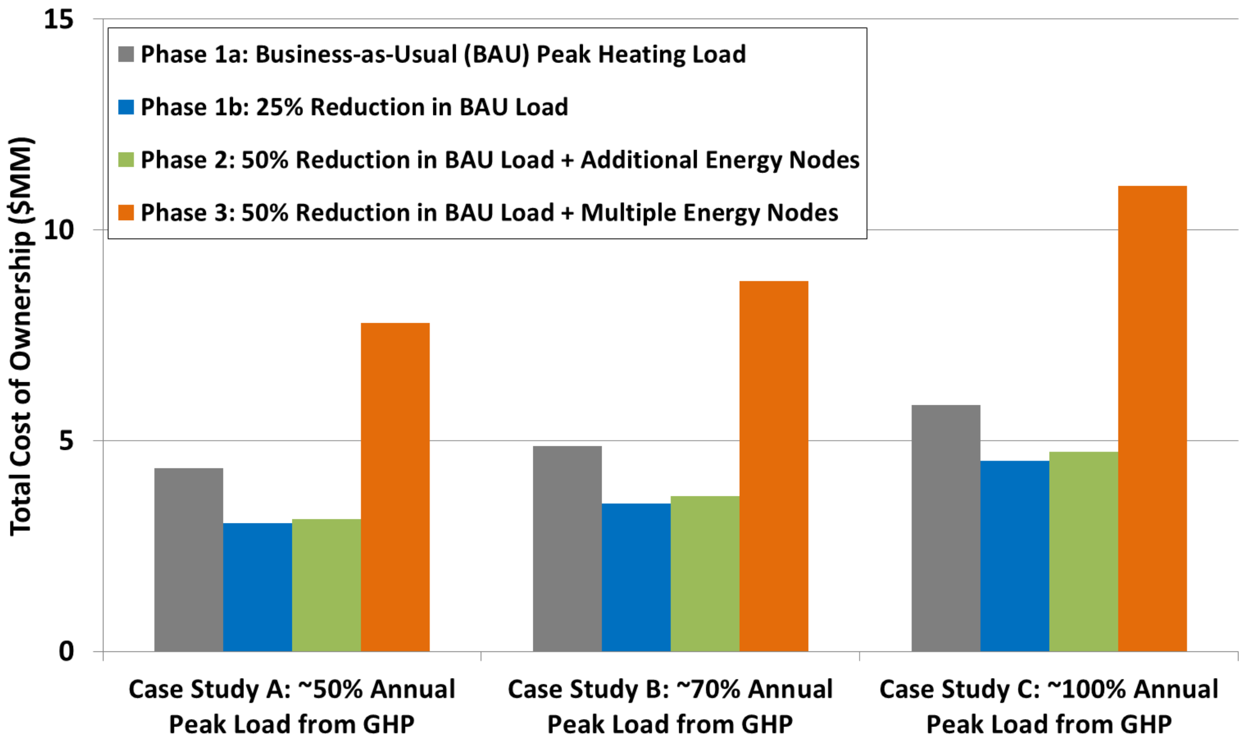

Figure 6.7 - Comparison of the total cost of ownership (TCO) of the GSDE network for all energy phases of case studies A, B, and C.

In Figure 6.8, the PB comparison of the GSDE network for all energy phases of case studies A, B, and C is provided. For case study A, the PB for all energy phases is in the range of 12 – 16 years, which is less than the estimated lifetime (20 years) of the GSDE network. For case study B, the PB for all energy phases is in the range of 15 – 19 years. The PB for all energy phases in case study C is in the range of 21 – 26 years, well above the estimated lifetime of the GSDE network.

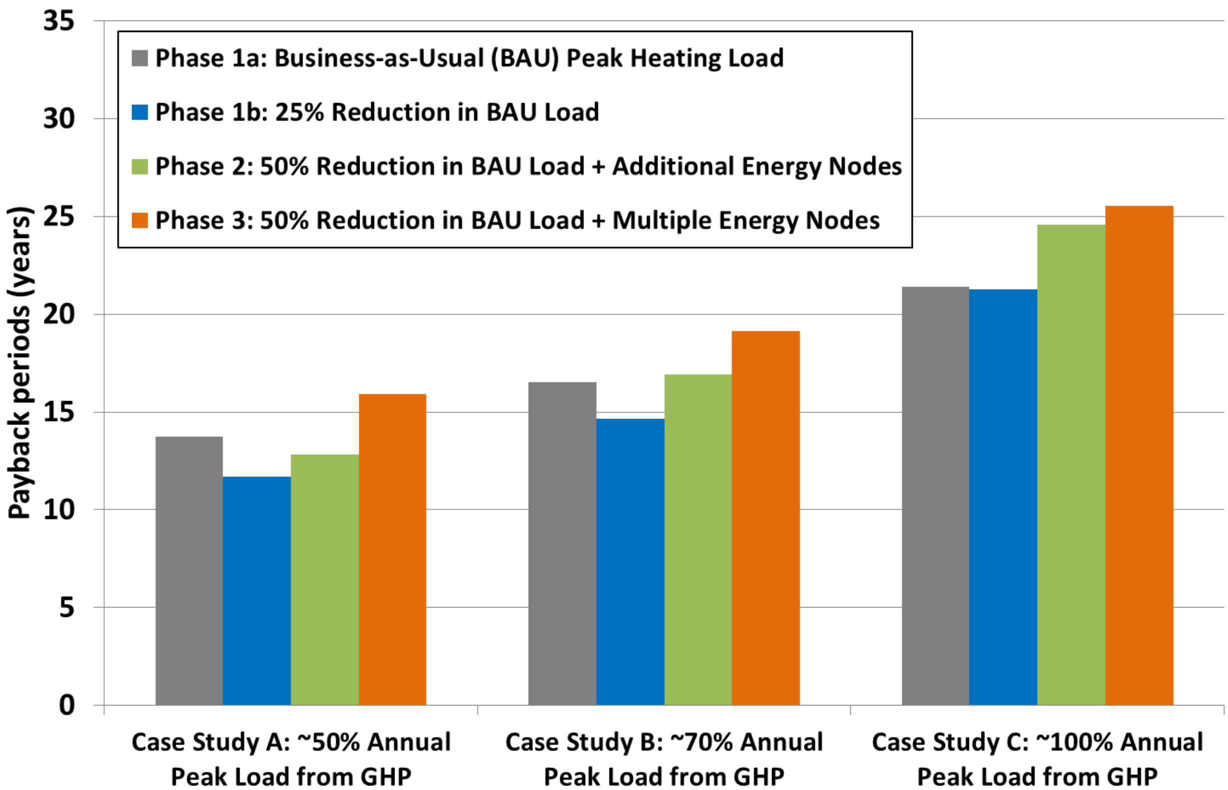

Figure 6.8 – Comparison of the payback period (PB) of the GSDE network for all energy phases of case studies A, B, and C.

Designing a geothermal system to cover 100% or more of the annual peak heating load is not economically viable because the system is overdesigned to cover peak demand that occurs only around 3 – 5% of the time in a given year. Furthermore, designing a geothermal system to cover between 50 – 70% of the peak load reduces costs and provides for heating 80 – 90% of the time in a given year (Bloomquist, 2003; Boyd, 2009).

From Figure 6.8, designing an energy system that provides around 50% of the annual peak heating load from geothermal resources and 50% from supplemental fossil fuel peak boilers (case study A) for all energy phases (1a, 1b, 2, and 3) appears to be the most attractive economic selection. However, phases that incorporate energy conservation measures and connect multiple energy nodes (phases 1b, 2, and 3) should be prioritized to ensure energy system designs that reduce energy waste and connect more consumers.

In Figure 6.9, the LCOH of the GSDE network for all energy phases of case studies A, B, and C is provided. The LCOH of case study A for all energy phases ranges from \$8.2/MMBtu - \$10.0/MMBtu. For case study B, the LCOH ranges from \$9.4/MMBtu - \$11.2/MMBtu. The LCOH of case study C ranges from \$10.4/MMBtu - \$11.5/MMBtu. According to Beckers (2016), a competitive LCOH for direct-use low-grade (<120°C) geothermal applications is between \$6/MMBtu - \$14/MMBtu.

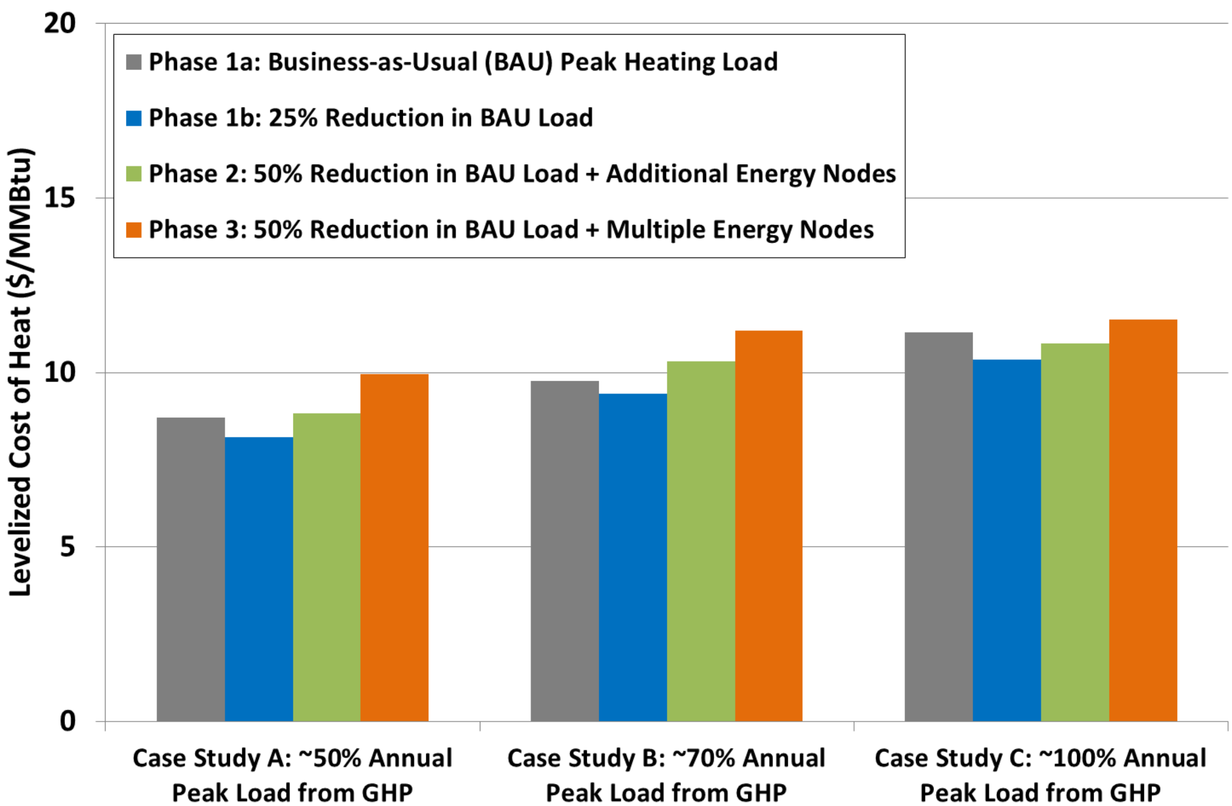

Figure 6.9 - Comparison of the levelized cost of heat (LCOH) of the GSDE network for all energy phases of case studies A, B, and C.

From figures 6.7 – 6.9, installing small GSDE networks for phases 1b and 2 designed to cover anywhere from 50 – 70% of the annual peak heating load of the area with geothermal resources appears economically feasible. Overall, the PB for phases 1b and 2 of case studies A and B are less than the expected lifetime of the GSDE network (20 years). Furthermore, the TCO for phases 1b and 2 of case studies A and B are the lowest (~ $3.5 million dollars), and the LCOH is in the competitive range of $8.2 - 10.3/MMBtu.

6.5: Conclusions and Recommendations

This chapter introduced the "GeoDistrict" tool to provide a first-order approximation of the technical and economic feasibility of shallow geothermal district energy systems (GSDE) at a community scale. The GeoDistrict tool considers the installation design of geothermal heat pump (GHP) systems in parking lots or vacant lots and the distribution design of the energy networks.

In this chapter, the GeoDistrict tool was employed within a small neighborhood in the downtown area of the City of Utica, NY that encompasses historic buildings, restaurants, and residential buildings. Several case studies on the feasibility of GSDE networks within the study area were assessed, and recommendations on the design and implementation of these systems were made. In addition, this chapter discussed revitalization opportunities for the City of Utica that includes building retrofitting, renewable energy development, and sustainable urban design.

Three case studies for the downtown area of Utica were assessed considering various scenarios that provide for the annual peak heating load demand of the area. Case studies A, B, and C consider the design of the geothermal fields to provide around 50%, 70%, and 100% of the area's heat load, respectively. For case studies A and B, the geothermal fields were designed to cover less than 100% of the area's heat load considering that annual peak demand generally occurs only around 3 – 5% of the time in a given year. In addition, three energy phases for each case study were assessed that consider business-as-usual peak load, reductions in building peak load, and additional energy networks to the original study area.

Summary case studies of the total cost of ownership (TCO), payback period (PB), and levelized cost of heat (LCOH) for GSDE installation in Utica, NY are presented in Table 6.63. For Case A, the TCO, PB, and LCOH for all energy phases range from \$3.1 million dollars - \$7.8 million dollars, 12 – 16 years, and \$8.2/MMBtu to \$10.0/MMBtu, respectively. For Case B, the TCO, PB, and LCOH for all energy phases range from \$3.5 million dollars - \$8.8 million dollars, 15 – 19 years, and \$9.4/MMBtu to \$11.2/MMBtu, respectively. For Case C, the TCO, PB, and LCOH for all energy phases range from \$4.5 million dollars - \$11.0 million dollars, 21 – 26 years, and \$10.4/MMBtu to \$11.5/MMBtu, respectively.

Table 6.63 – Summary of the total cost of ownership, payback period, and levelized cost of heat for GSDE case studies involving various energy phases in Utica, NY.

Case Study	Total Cost of Ownership (\$MM)	Payback Period (Years)	Levelized Cost of Heat (\$/MMBtu)
Case A	\$3.1 - \$7.8	12 - 16	\$8.2 - \$10.0
Case B	\$3.5 - \$8.8	15 - 19	\$9.4 - \$11.2
Case C	\$4.5 - \$11.0	21 - 26	\$10.4 - \$11.5

From the analysis in sections 6.4.1 – 6.4.4 and Table 6.63, designing a geothermal system to meet 100% of the annual peak heating load (Case C) of the area does not result in a feasible economic option because the payback period surpasses the expected GSDE system lifetime of 20 years. Instead, designing a geothermal system to cover 50 – 70% of the peak load (cases A and B) results in an economically viable option for all the energy phases provided in sections 6.4.1 –

6.4.4. Furthermore, installing GSDE networks for energy phases that address retrofitting measures to reduce building peak load appears as the most techno-economically feasible option discussed in this chapter.

The GeoDistrict tool discussed in this chapter serves only as a first-order approximation of the techno-economic feasibility of installing GSDE networks in small to mid-size communities. The tool does not include detailed building heat load estimates for all of the buildings considered within the study area. In addition, building retrofitting recommendations provided by Prathibha (2016) are not included in the model(s) and should be considered on a building-by-building basis. The GeoDistrict tool does not include recommendations on sustainable neighborhood design nor on the solar energy potential options within the study area provided by Moreno-Long (2016) and Sud (2016), respectively.

Future work should encompass performing a detailed building-by-building heat load assessment and energy conservation measures for all the buildings within the study area prior to GSDE installation. In addition, future work could incorporate building-by-building cost estimates of retrofitting options and energy cost savings from replacing inefficient heating and cooling systems with energy-efficient geothermal technologies.

Other recommendations for future work include assessing sustainable neighborhood development in Utica as an integrated systems approach incorporating key elements on revitalizing and transforming sustainable communities in New York State (Reber et al., 2013). From Reber et al. (2013), key elements to consider for systems-based integration include energy, food, water, waste, urban design, transportation, buildings, business and economic development, and governance and communication.

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CHAPTER 7

DISSERTATION CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Dissertation Objectives and Organization

The first objective of the dissertation was to assess the technical, economic, and environmental performance (TEEP) of hybrid geothermal heat pump (GHP) and air-source heat pump (ASHP) systems for cooling of cellular tower shelters nationwide. The second objective was to develop an integrative framework and tool to assess the technical and economic performance of shallow geothermal (GHP) district energy systems (GSDE) at a neighborhood scale.

The dissertation was divided into two parts with four major sections corresponding to seven chapters. Part I introduced GHP systems and their utilization potential for cooling-dominated applications nationwide. Part II introduced the GSDE framework and tool for sustainable development in small-to-mid-size communities. The four major sections include Chapters 1 and 2; Chapters 3 and 4; Chapters 5 and 6; and Chapter 7.

Chapters 1 and 2 provided an introduction to the dissertation and the analysis. Chapter 3 introduced GHP systems for cooling-dominated applications. Chapter 4 presented the systems engineering model (SEM) to assess the TEEP of hybrid GHP and ASHP systems, provided case studies and a sensitivity analysis of the TEEP for five cooling configurations nationwide. Chapter 5 introduced GSDE systems for sustainable neighborhood development. Chapter 6 presented an integrative framework and tool for the adoption of GSDE systems in small-to-mid-size communities with case studies for a neighborhood in Utica, NY. Chapter 7 provided the conclusions of the dissertation, and recommendations for future work. What follows are the main results, conclusions, and recommendations for future work from chapters 3 – 6.

Chapters 3 and 4: Utilization Potential of Hybrid GHP and ASHP systems for Cooling-Dominated Applications Nationwide

Chapter 3 provided an introduction to GHP technology, and the utilization potential of hybrid GHP systems for cooling-dominated applications. The chapter discussed the major components of a GHP system including ground loop (BHE) connection, heat pump system, and air distribution system. Configuration designs of hybrid GHPs in cooling mode, including air-side economizers (AE) and dry-coolers (DC), were discussed as options to thermally balance the BHE fields over the lifetime of the system (20 years).

Chapter 4 provided an introduction to the SEM to assess the TEEP of hybrid GHP and ASHP systems for cooling of cellular tower shelters nationwide. Case studies evaluating the TEEP for five cooling configurations were provided. The five cooling configurations consider: 1) GHP-only; 2) GHP + AE; 3) GHP + DC; 4) ASHP-only; and 5) ASHP + AE. In addition, a sensitivity analysis assessed the influence on the TEEP of five cooling configurations from variability in the technical and financial parameters of the model.

For the five cooling configurations, the SEM output involved nationwide comparison of the total cost of ownership (TCO), lifetime electricity consumption (LEC), and lifetime CO_2-equivalent emissions (LCO_2e). The TEEP performance for all case studies were summarized based on climatic regions from the annual mean surface temperature of a typical meteorological year (TMY3) database. For case 1 (GHP-only), weather boundaries located in cool climates (e.g., Maine and Minnesota) result in small geothermal BHE fields (up to 280 m of total BHE length), and TCO in the range of \$45,000 - \$67,700. For warm climatic regions (e.g., California and Florida), a higher number of boreholes and/or longer borehole depths is required (over 1,000 m of total BHE length for some regions). The TCO for warm climatic regions is in the range of \$60,700 - \$96,900. The size of the BHE field affects the TCO, which includes the capital costs and lifetime operating and maintenance costs of the BHE field and GHP equipment.

For case 2 (GHP + AE), the use of AE benefit weather boundaries located in cool climates because cool air is allowed to flow into the shelter reducing the cooling demand in the GHP system. A lower cooling demand in the GHP system results in smaller BHE field installations; therefore, reducing overall costs and LEC/LCO_2e emissions. In contrast, the benefits of using AE units in regions with warm climates are lower because warm temperatures reduce the potential use and frequency of hybrid GHP systems.

For case 3 (GHP + DC), coupling the GHP system with DC units in all climatic regions result in a decrease of the BHE field compared to case 1. For regions with cool climates, the decrease in the total BHE length for case 3 is up to 60% compared to case 1. For warm climatic regions, the decrease in the total BHE length for case 3 is up to 50% compared to case 1. However, LEC for case 3 is higher than cases 1 and 2 for all climatic regions because the DC is used significantly throughout the year. Even though case 3 results in smaller BHE field installations compared to cases 1 and 2, the operating costs and LEC/LCO_2e emissions for case 3 are the highest of all GHP configurations.

For case 4 (ASHP), the TCO, LEC, and LCO_2e emissions are higher in region with high cooling loads because more electricity is consumed over the lifetime of the system. Similar to case 2, the use of AE units in case 5 (ASHP+AE) benefit cool climatic regions the most because cool air flowing into the shelter reduces the load in the hybrid ASHP.

The sensitivity analysis presented in this chapter considered the TEEP influence from one-at-a-time variations of technical and financial parameters across geographic locations in various climatic regions. For GHP cases, the TEEP impacts of increasing the total BHE length in regions with cool climates are more favorable than in warm climates because of improve GHP system performance (COP) resulting in reductions of LEC and TCO. Similarly, the TEEP impacts of variations in the thermal conductivity of the BHE field affects the performance and costs of weather boundaries located in cool climates the most. Warm climatic regions involve large BHE field size installations; therefore, changes in the total BHE lengths or in the thermal field properties have less of an effect on the overall performance and costs in these regions.

For the TCO sensitivity of financial parameters, the drilling cost variability was significant in regions with large BHE fields (e.g., Florida), and minimal in regions with small BHE fields (e.g., Maine). For operating cost variability, the TCO sensitivity is high in regions with coupled high LEC and electricity rates (e.g., California).

Furthermore, installation and maintenance costs of GHP systems appear to have the least effect on the TCO of GHPs for all geographic locations. For ASHP systems, significant increases in the maintenance costs are likely to result in higher TCO because ASHPs incur a higher annual maintenance cost than GHPs.

With the use of GHP systems, regions with high electricity prices and electricity consumption will experience lower costs and environmental impacts from a reduction in operating conditions over the lifetime of the system. If incentives are considered in the base case scenario of GHP systems, large reductions in the TCO for all locations are observed increasing the attractiveness of implementing energy-efficient technology.

The base case results presented in Chapter 4 provide an approximation of the performance of five cooling configurations in various locations across the U.S. for cooling of cell tower shelters. To increase the accuracy and the spatial resolution at a particular location, it is recommended to perform a detailed hydrogeological and climatic analysis and consider available incentives and rebates for energy-efficient technologies.

For instance, the nationwide hydrogeological characterization of GHP systems presented in Section 4.2.4 considers indirect methods to assess the ground thermal properties of the site. Due to the complexities of performing thermal response tests (TRT) or laboratory measurements nationwide, the hydrogeological characterizations provided in Chapter 4 only represent first-order approximations of the site thermal properties. To increase the characterization of site-specific BHE fields, TRT and laboratory measurements on individual boreholes should be performed prior to the design of GHP systems. In addition, the TMY3 weather dataset employed in Section 4.2.2 represents typical rather than extreme weather conditions. Therefore, the design of the hybrid GHP and ASHP systems provided in Chapter 4 are not representative of peak load conditions and/or worst-case scenarios.

Current barriers to increased market penetration of GHP systems include lack of awareness and/or distrust in the systems benefits, lack of experienced designers and installers, high capital costs, and uncertain return on investment (ROI). Even though GHP systems have longer expected lifetimes (over 20 years) and incur lower maintenance and operating costs compared to ASHPs, the biggest barrier to faster ROIs is the capital costs from ground loop drilling operations.

For cooling-dominated applications in warm climates, reductions in the drilling costs will make GHP systems more attractive. Furthermore, it is expected that with consideration of incentives and rebates, increasing electricity rates, and possible carbon taxes, the investment in GHP systems will be more favorable in the future than in today's economy. Because incentives and rebates may vary from year-to-year, it is recommended to search for any relevant opportunities in the databases provided in Section 4.2.5 before the installation of energy-efficient technologies.

Chapters 5 and 6: Shallow Geothermal District Energy Systems (GSDE) for Sustainable Neighborhood Development

Chapter 5 provided an introduction to GSDE systems, and their potential application in small-to-mid-size communities for space heating and cooling. The chapter discussed the major components of district energy systems including energy production, energy distribution, and energy consumption. In addition, Chapter 5 provided several case studies on recent GSDE development in college campuses and municipalities across the Midwestern and Northeastern U.S.

Chapter 6 introduced the development of the "GeoDistrict" tool to provide a first-order approximation of the technical and economic feasibility of GSDE at a community scale. The GeoDistrict tool considers the installation design of GHP systems in parking lots or vacant lots, and the distribution design of the energy networks to the end-users. In Chapter 6, the

GeoDistrict tool was employed within a small neighborhood in the downtown area of the City of Utica, NY that encompasses historic buildings, restaurants, and residential buildings.

Three case studies (A, B, and C) were assessed for the downtown area of Utica considering various energy phase scenarios (1a, 1b, 2, and 3) to provide for the annual peak heating load of the area. Case studies A, B, and C consider the design of the geothermal fields to provide around 50%, 70%, and 100% of the area's annual peak heating load, respectively. For cases designed to cover a portion of the annual peak heating load of the area, the remainder load is covered by a supplemental natural gas peak boiler.

Energy phase 1a involves business-as-usual (BAU) peak load demand for the study area. Energy phase 1b considers the effect of a 25% reduction in peak load demand from BAU. Energy phase 2 considers a 50% reduction in peak load demand from BAU and additional adjacent energy nodes. Energy phase 3 also considers a 50% reduction in peak load demand from BAU plus the addition of multiple energy nodes extending outside of the original study area.

For case study A providing around 50% of the annual peak heating load with geothermal resources, the capital (CAP) costs for the entire GSDE network for all energy phases ranges from $1.0 million dollars – $2.8 million dollars. The payback period (PB) and levelized cost of heat (LCOH) for all energy phases ranges from 12 – 16 years and $8.2/MMBtu – $10/MMBtu, respectively.

For all energy phases of case study B, the CAP costs for the entire GSDE network ranges from $1.3 million dollars – $3.4 million dollars. The PB and LCOH ranges from 15 – 19 years and $9.4/MMBtu – $11.2/MMBtu, respectively. For all energy phases of case study C, the CAP costs for the entire GSDE network ranges from \$1.9 million dollars – \$4.5 million dollars. The PB and LCOH for all energy phases of case study C ranges from 21 – 26 years and \$10.4/MMBtu – \$11.5/MMBtu, respectively.

Overall, all of the energy phases considered in case study A result in a PB less than the expected GSDE system lifetime (20 years), and in a LCOH that is competitive for direct-use low-grade geothermal applications (\$6/MMBtu - \$14/MMBtu; Beckers, 2016). The costs, PB, and LCOH for case study B are expected to be higher than for case study A because of larger and/or additional geothermal fields required to provide for the expected 70% annual peak load. The PB for all energy phases of case study C is over the expected lifetime of the GSDE network (20 years), which is not an attractive ROI.

The GeoDistrict tool discussed in Chapter 6 serves only as a first-order approximation of the techno-economic feasibility of installing GSDE networks in small to mid-size communities. The tool does not include detailed building heat load estimates for all of the buildings considered within the study area. In addition, building retrofitting recommendations provided by Prathibha (2016) are not included in the model and should be considered on a building-by-building basis. The GeoDistrict tool does not include recommendations on sustainable neighborhood design nor on the solar energy potential options within the study area provided by Moreno-Long (2016) and Sud (2016), respectively.

Future work should encompass performing a detailed building-by-building heat load assessment and energy conservation measures for all the buildings within the study area prior to GSDE installation. In addition, future work could incorporate building-by-building cost estimates for various retrofitting options, and comparison of the energy cost savings from replacing inefficient heating and cooling systems with energy-efficient technologies. Further recommendations include assessing sustainable neighborhood development in Rust Belt Cities as an integrated systems approach incorporating key elements on revitalizing and transforming sustainable communities (Reber et al., 2013).

APPENDIX A

SUPPORTING DOCUMENTATION

CHAPTER 4: HYBRID GEOTHERMAL HEAT PUMPS FOR COOLING CELLULAR TOWER SHELTERS

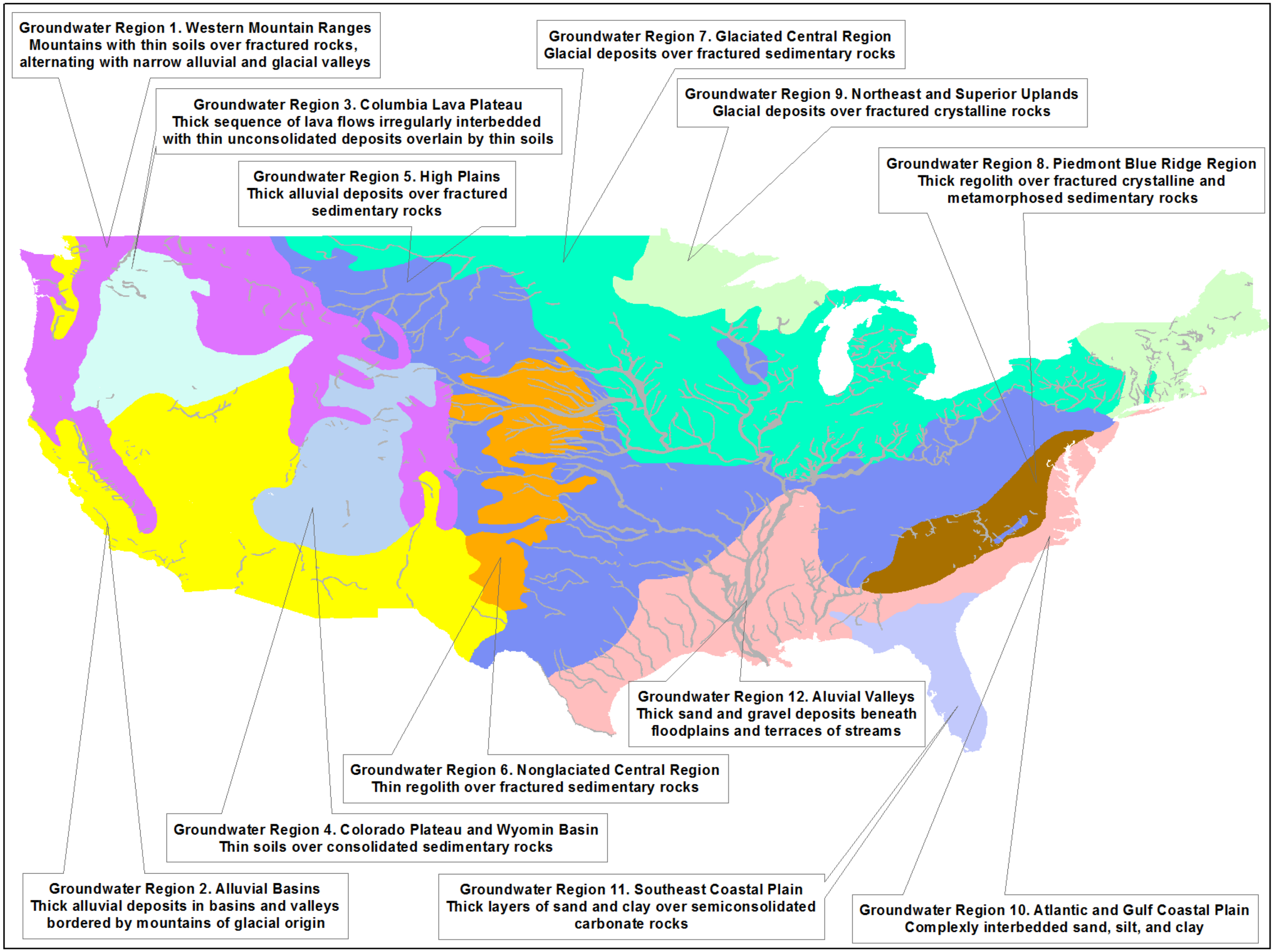


Figure A.1 - Geological and hydrological characteristics of twelve groundwater regions presented by Thomas (1952) and Heath (1984).

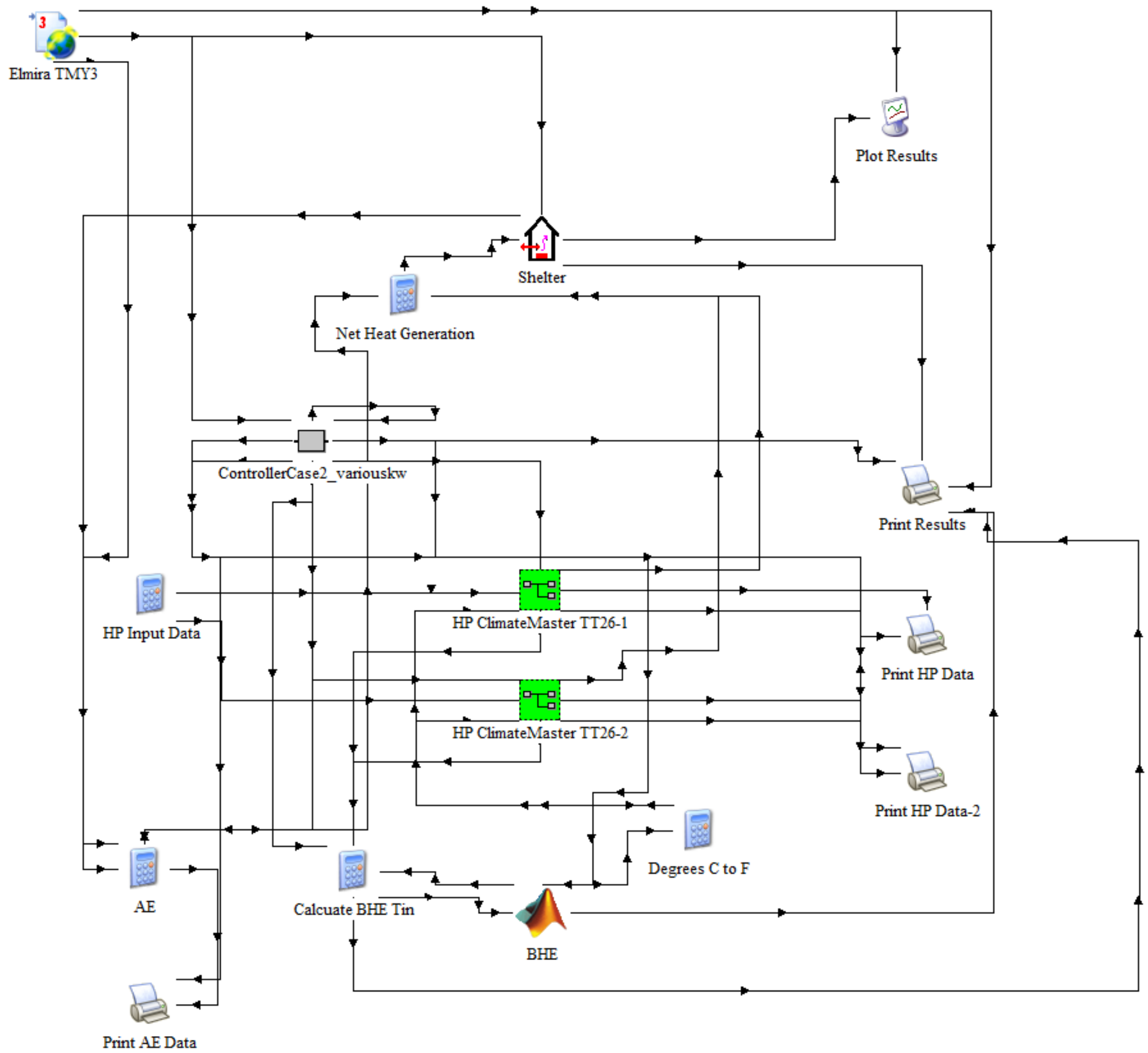


Figure A.2 – Schematic of the TRNSYS model for case 2: GHP + AE for cooling of cellular tower shelters (Beckers, 2016).

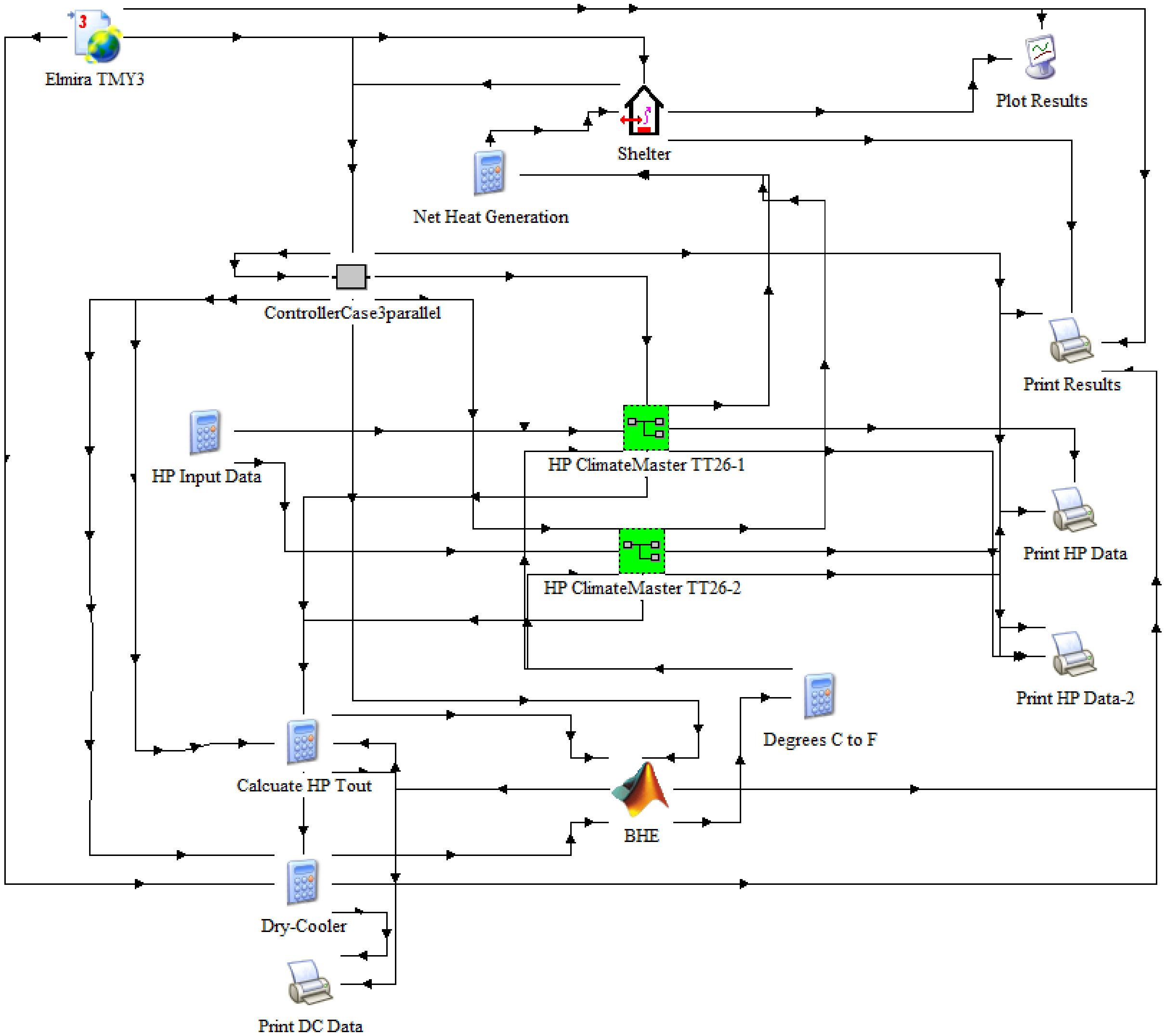


Figure A.3 – Schematic of the TRNSYS model for case 3: GHP + DC for cooling of cellular tower shelters (Beckers, 2016).

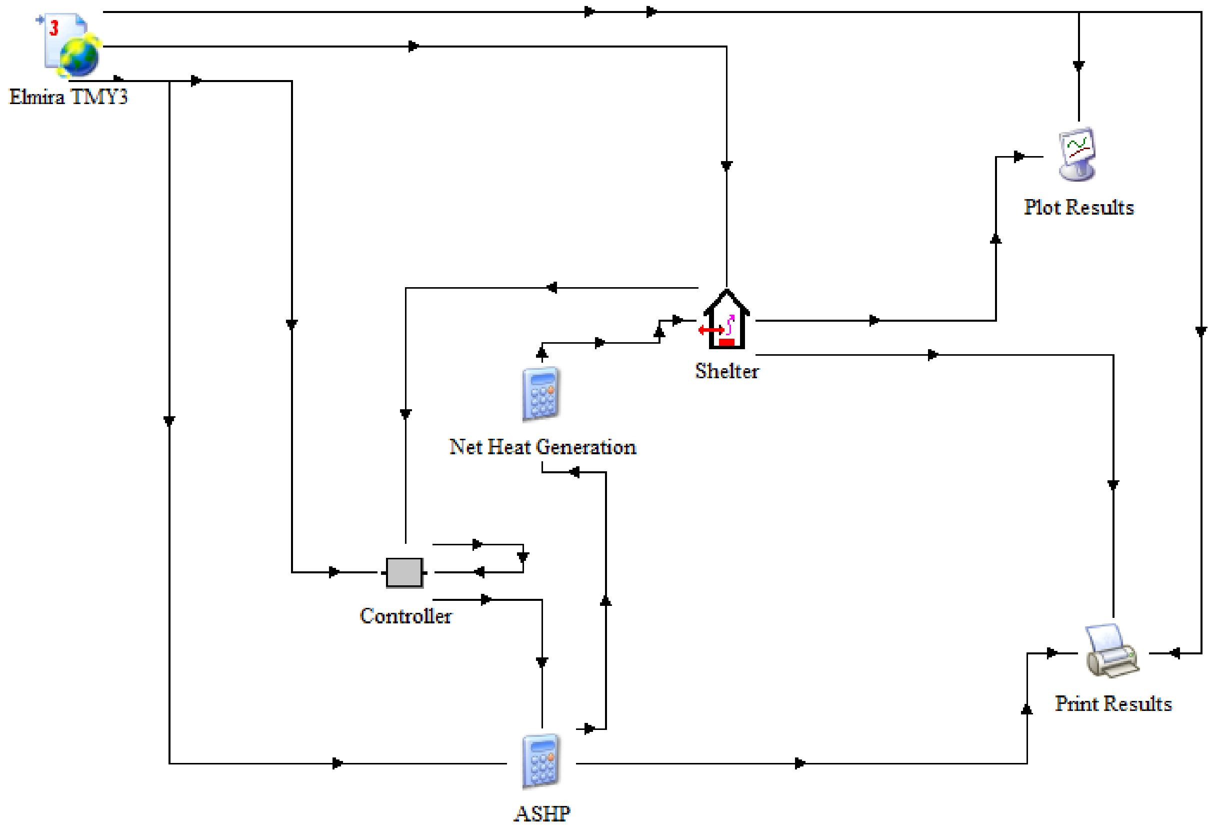


Figure A.4 – Schematic of the TRNSYS model for case 4: ASHP for cooling of cellular tower shelters (Beckers, 2016).

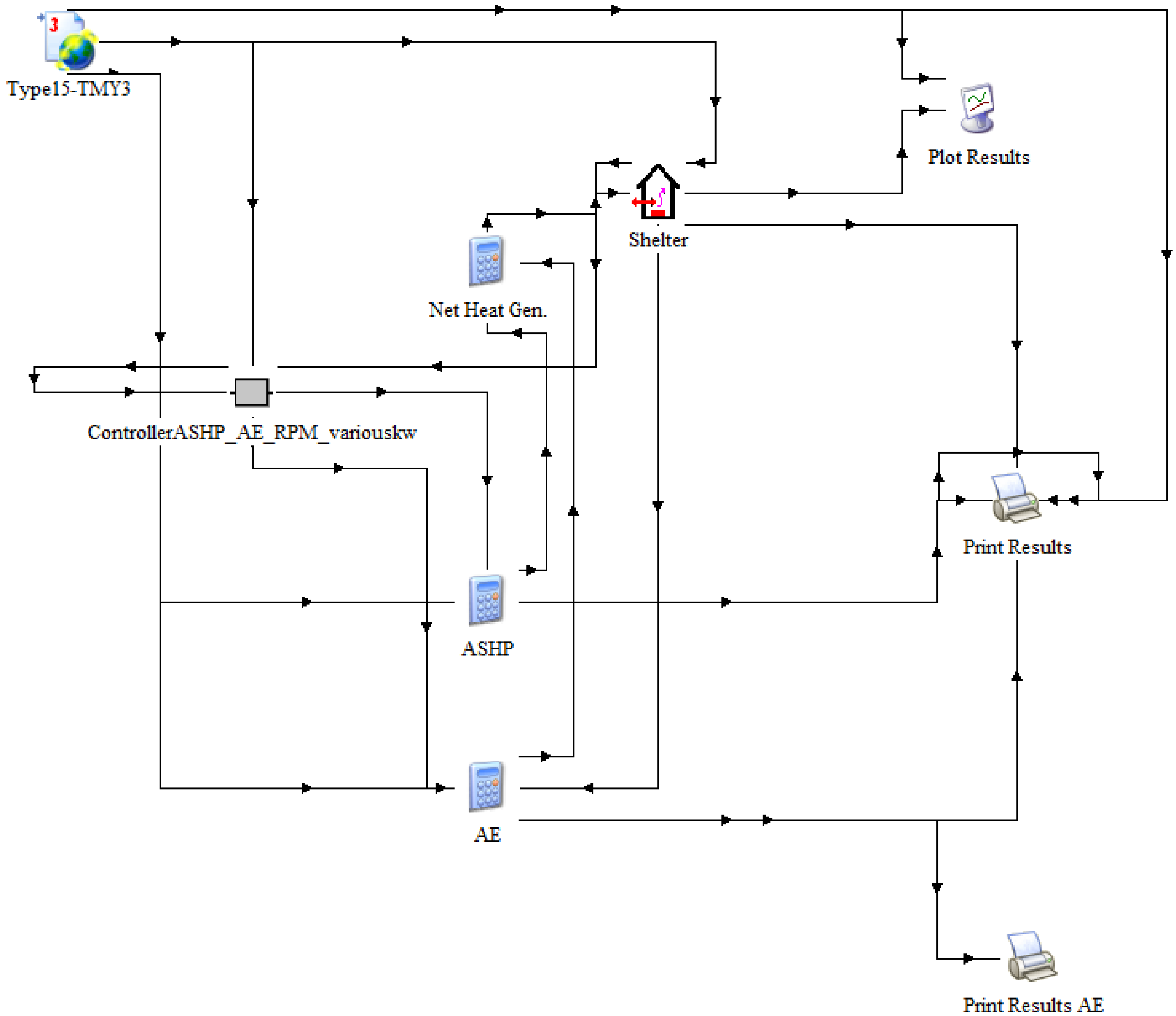


Figure A.5 – Schematic of the TRNSYS model for case 5: ASHP + AE for cooling of cellular tower shelters (Beckers, 2016).

Table A.1 – Summary of Technical Parameter Sensitivity Analysis for Case 1: GHP – only in Varna, NY.

	Sensitivity Analysis - Case 1: GHP; Location: Varna, NY					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 110 m = 220 m	61.3	26.6	34.7	347.6	64.8	3.8
Thermal Conductivity (Base Case), Kf,s = 2.2 W/mK	61.3	26.6	34.7	347.6	64.8	3.8
Total BHE Length (Increase), 2 x 125 m = 250 m	59.3	28.1	31.2	308.3	57.4	4.3
Total BHE Length (Increase), 3 x 110 m = 330 m	59.8	32.4	27.4	267.1	49.8	4.9
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	86.9	26.6	60.3	625.8	116.6	2.1
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	52.3	26.6	25.8	247.9	46.2	5.3
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	49.1	26.6	22.5	211.5	39.4	6.3

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 110 m = 220 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.2 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 125 m = 250 m	-3.2	5.9	-10.2	-11.3	-11.3	12.8
Total BHE Length (Increase), 3 x 110 m = 330 m	-2.5	21.8	-21.0	-23.2	-23.2	30.1
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	41.8	0.0	73.8	80.0	80.0	-44.5
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	-14.6	0.0	-25.7	-28.7	-28.7	40.2
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-20.0	0.0	-35.2	-39.2	-39.2	64.4

Table A.2 – Summary of Technical Parameter Sensitivity Analysis for Case 1: GHP – only in Caribou, ME.

	Sensitivity Analysis - Case 1: GHP; Location: Caribou, ME					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 65 m = 130 m	56.1	21.8	34.2	353.8	103.3	3.7
Thermal Conductivity (Base Case), Kf,s = 3.0 W/mK	56.1	21.8	34.2	353.8	103.3	3.7
Total BHE Length (Increase), 2 x 75 m = 150 m	52.3	22.9	29.4	298.3	87.1	4.3
Total BHE Length (Increase), 2 x 100 m = 200 m	49.1	25.5	23.6	232.1	67.7	5.6
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	81.6	21.8	59.8	634.4	185.1	2.0
Thermal Conductivity (Increase), Kf,s = 4.6 W/mK	47.3	21.8	25.4	252.3	73.6	5.1
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	43.9	21.8	22.1	214.0	62.5	6.1

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 65 m = 130 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 3.0 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 75 m = 150 m	-6.8	4.8	-14.2	-15.7	-15.7	18.6
Total BHE Length (Increase), 2 x 100 m = 200 m	-12.4	16.9	-31.1	-34.4	-34.4	52.5
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	45.6	0.0	74.6	79.3	79.3	-44.2
Thermal Conductivity (Increase), Kf,s = 4.6 W/mK	-15.7	0.0	-25.8	-28.7	-28.7	40.2
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	-21.7	0.0	-35.6	-39.5	-39.5	65.3

Table A.3 – Summary of Technical Parameter Sensitivity Analysis for Case 1: GHP – only in Minneapolis, MN.

	Sensitivity Analysis - Case 1: GHP; Location: Minneapolis, MN					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 110 m = 220 m	48.1	24.4	23.7	281.8	183.4	4.7
Thermal Conductivity (Base Case), Kf,s = 2.6 W/mK	48.1	24.4	23.7	281.8	183.4	4.7
Total BHE Length (Increase), 2 x 125 m = 250 m	47.6	25.7	21.9	257.0	167.2	5.1
Total BHE Length (Increase), 3 x 110 m = 330 m	49.1	29.1	20.0	230.4	149.9	5.7
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	72.5	24.4	48.2	614.4	399.8	2.1
Thermal Conductivity (Increase), Kf,s = 4.5 W/mK	43.6	24.4	19.2	219.2	142.6	6.0
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	42.3	24.4	17.9	201.4	131.1	6.5

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 110 m = 220 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.6 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 125 m = 250 m	-1.1	5.2	-7.6	-8.8	-8.8	9.6
Total BHE Length (Increase), 3 x 110 m = 330 m	1.9	19.2	-15.8	-18.2	-18.2	22.3
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	50.7	0.0	102.8	118.0	118.0	-54.1
Thermal Conductivity (Increase), Kf,s = 4.5 W/mK	-9.4	0.0	-19.0	-22.2	-22.2	28.6
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-12.1	0.0	-24.5	-28.5	-28.5	39.9

Table A.4 – Summary of Technical Parameter Sensitivity Analysis for Case 1: GHP – only in Denver, CO.

	Sensitivity Analysis - Case 1: GHP; Location: Denver, CO					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 135 m = 270 m	52.3	28.0	24.3	296.2	246.4	4.5
Thermal Conductivity (Base Case), Kf,s = 2.4 W/mK	52.3	28.0	24.3	296.2	246.4	4.5
Total BHE Length (Increase), 2 x 150 m = 300 m	52.3	29.4	22.9	276.3	229.8	4.8
Total BHE Length (Increase), 3 x 135 m = 405 m	55.3	34.5	20.9	248.2	206.4	5.4
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	72.1	28.0	44.2	579.4	481.9	2.3
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	48.6	28.0	20.6	244.1	203.0	5.5
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	46.3	28.0	18.3	212.0	176.3	6.3

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 135 m = 270 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.4 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 150 m = 300 m	0.1	5.2	-5.8	-6.7	-6.7	7.2
Total BHE Length (Increase), 3 x 135 m = 405 m	5.8	23.2	-14.1	-16.2	-16.2	19.3
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	38.0	0.0	81.8	95.6	95.6	-48.9
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	-7.0	0.0	-15.1	-17.6	-17.6	21.3
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	-11.4	0.0	-24.5	-28.4	-28.4	39.8

Table A.5 – Summary of Technical Parameter Sensitivity Analysis for Case 1: GHP – only in Sacramento, CA.

	Sensitivity Analysis - Case 1: GHP; Location: Sacramento, CA					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 3 x 120 m = 360 m	69.4	32.3	37.1	321.6	95.3	4.2
Thermal Conductivity (Base Case), Kf,s = 2.5 W/mK	69.4	32.3	37.1	321.6	95.3	4.2
Total BHE Length (Increase), 3 x 135 m = 405 m	69.5	34.5	35.1	302.1	89.5	4.5
Total BHE Length (Increase), 4 x 135 m = 540 m	73.1	40.9	32.2	275.0	81.5	4.9
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	95.0	32.3	62.7	570.8	169.2	2.4
Thermal Conductivity (Increase), Kf,s = 4.0 W/mK	63.9	32.3	31.6	268.8	79.7	5.0
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	61.3	32.3	29.0	243.9	72.3	5.5

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 3 x 120 m = 360 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.5 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 3 x 135 m = 405 m	0.2	6.7	-5.4	-6.0	-6.0	6.4
Total BHE Length (Increase), 4 x 135 m = 540 m	5.4	26.8	-13.1	-14.5	-14.5	16.9
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	36.9	0.0	69.0	77.5	77.5	-43.7
Thermal Conductivity (Increase), Kf,s = 4.0 W/mK	-7.9	0.0	-14.7	-16.4	-16.4	19.6
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-11.6	0.0	-21.7	-24.2	-24.2	31.8

Table A.6 – Summary of Technical Parameter Sensitivity Analysis for Case 1: GHP – only in Miami, FL.

	Sensitivity Analysis - Case 1: GHP; Location: Miami, FL					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 8 x 135 m = 1080 m	96.9	67.9	29.0	361.5	185.4	3.9
Thermal Conductivity (Base Case), Kf,s = 2.1 W/mK	96.9	67.9	29.0	361.5	185.4	3.9
Total BHE Length (Increase), 8 x 150 m = 1200 m	102.2	73.8	28.4	353.2	181.2	4.0
Total BHE Length (Increase), 10 x 150 m = 1500 m	116.0	88.5	27.5	340.4	174.6	4.1
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	102.1	67.9	34.1	436.5	223.9	3.2
Thermal Conductivity (Increase), Kf,s = 4.1 W/mK	94.2	67.9	26.2	322.1	165.2	4.3
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	93.3	67.9	25.4	309.9	159.0	4.5

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 8 x 135 m = 1080 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.1 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 8 x 150 m = 1200 m	5.5	8.7	-2.0	-2.3	-2.3	2.4
Total BHE Length (Increase), 10 x 150 m = 1500 m	19.7	30.3	-5.1	-5.9	-5.9	6.2
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	5.3	0.0	17.8	20.7	20.7	-17.2
Thermal Conductivity (Increase), Kf,s = 4.1 W/mK	-2.8	0.0	-9.4	-10.9	-10.9	12.2
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-3.7	0.0	-12.3	-14.3	-14.3	16.6

Table A.7 – Summary of Technical Parameter Sensitivity Analysis for Case 2: GHP + AE in Varna, NY.

	Sensitivity Analysis - Case 2: GHP+AE; Location: Varna, NY					
Technical Parameter	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 90 m = 180 m	45.8	25.5	20.3	156.5	29.1	4.1
Thermal Conductivity (Base Case), Kf,s = 2.2 W/mK	45.8	25.5	20.3	156.5	29.1	4.1
Air Economizer Setpoint (Base Case), Tae = 10°C	45.8	25.5	20.3	156.5	29.1	4.1
Air Economizer Setpoint (Decrease), Tae = 5°C	52.4	25.5	26.9	228.9	42.6	3.7
Air Economizer Setpoint (Increase), Tae = 15°C	40.5	25.5	15.1	98.8	18.4	4.6
Total BHE Length (Increase), 2 x 100 m = 200 m	45.6	26.5	19.1	143.0	26.6	4.5
Total BHE Length (Increase), 2 x 135 m = 270 m	47.0	30.2	16.8	117.8	21.9	5.5
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	56.6	25.5	31.1	274.5	51.1	2.3
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	42.4	25.5	16.9	118.8	22.1	5.4
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	41.0	25.5	15.6	104.2	19.4	6.2

	% Change From Base Case Estimates					
Technical Parameter	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 90 m = 180 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.2 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Base Case), Tae = 10°C	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Decrease), Tae = 5°C	14.4	0.0	32.5	46.3	46.3	-9.3
Air Economizer Setpoint (Increase), Tae = 15°C	-11.5	0.0	-25.9	-36.8	-36.8	12.0
Total BHE Length (Increase), 2 x 100 m = 200 m	-0.4	4.1	-6.1	-8.6	-8.6	9.6
Total BHE Length (Increase), 2 x 135 m = 270 m	2.6	18.6	-17.4	-24.7	-24.7	33.4
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	23.6	0.0	53.2	75.4	75.4	-43.3
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	-7.5	0.0	-16.8	-24.1	-24.1	32.2
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-10.4	0.0	-23.4	-33.4	-33.4	51.1

Table A.8 – Summary of Technical Parameter Sensitivity Analysis for Case 2: GHP + AE in Caribou, ME.

	Sensitivity Analysis - Case 2: GHP+AE; Location: Caribou, ME					
Technical Parameter	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 50 m = 100 m	38.5	21.3	17.3	126.8	37.0	3.7
Thermal Conductivity (Base Case), Kf,s = 3.0 W/mK	38.5	21.3	17.3	126.8	37.0	3.7
Air Economizer Setpoint (Base Case), Tae = 10°C	38.5	21.3	17.3	126.8	37.0	3.7
Air Economizer Setpoint (Decrease), Tae = 5°C	44.7	21.3	23.5	197.1	57.5	3.4
Air Economizer Setpoint (Increase), Tae = 15°C	33.6	21.3	12.3	71.2	20.8	4.3
Total BHE Length (Increase), 2 x 55 m = 110 m	37.9	21.8	16.1	113.5	33.1	4.2
Total BHE Length (Increase), 2 x 75 m = 150 m	37.4	23.9	13.6	85.2	24.9	5.6
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	47.4	21.3	26.1	225.7	65.9	2.1
Thermal Conductivity (Increase), Kf,s = 4.6 W/mK	35.7	21.3	14.5	95.4	27.9	5.0
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	34.6	21.3	13.4	82.8	24.2	5.7

	% Change from Base Case Estimates					
Technical Parameter	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 50 m = 100 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 3.0 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Base Case), Tae = 10°C	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Decrease), Tae = 5°C	16.2	0.0	36.1	55.4	55.4	-9.5
Air Economizer Setpoint (Increase), Tae = 15°C	-12.8	0.0	-28.7	-43.8	-43.8	15.9
Total BHE Length (Increase), 2 x 55 m = 110 m	-1.7	2.5	-6.9	-10.5	-10.5	11.9
Total BHE Length (Increase), 2 x 75 m = 150 m	-2.8	12.4	-21.4	-32.8	-32.8	49.9
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	23.1	0.0	51.5	78.0	78.0	-44.2
Thermal Conductivity (Increase), Kf,s = 4.6 W/mK	-7.2	0.0	-16.1	-24.7	-24.7	33.4
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	-10.1	0.0	-22.6	-34.7	-34.7	54.3

Table A.9 – Summary of Technical Parameter Sensitivity Analysis for Case 2: GHP + AE in Minneapolis, MN.

	Sensitivity Analysis - Case 2: GHP+AE; Location: Minneapolis, MN					
Technical Parameter	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 90 m = 180 m	39.3	23.7	15.7	131.0	85.2	4.8
Thermal Conductivity (Base Case), Kf,s = 2.6 W/mK	39.3	23.7	15.7	131.0	85.2	4.8
Air Economizer Setpoint (Base Case), Tae = 10°C	39.3	23.7	15.7	131.0	85.2	4.8
Air Economizer Setpoint (Decrease), Tae = 5°C	42.2	23.7	18.5	170.2	110.8	4.6
Air Economizer Setpoint (Increase), Tae = 15°C	36.9	23.7	13.2	98.1	63.8	5.0
Total BHE Length (Increase), 2 x 100 m = 200 m	39.5	24.5	14.9	121.4	79.0	5.2
Total BHE Length (Increase), 2 x 135 m = 270 m	41.2	27.5	13.7	103.7	67.5	6.1
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	49.6	23.7	25.9	270.5	176.0	2.3
Thermal Conductivity (Increase), Kf,s = 4.5 W/mK	37.4	23.7	13.8	105.2	68.4	6.0
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	36.9	23.7	13.2	97.7	63.6	6.4

	% Change from Base Case Estimates					
Technical Parameter	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 90 m = 180 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.6 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Base Case), Tae = 10°C	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Decrease), Tae = 5°C	7.3	0.0	18.5	30.0	30.0	-4.5
Air Economizer Setpoint (Increase), Tae = 15°C	-6.2	0.0	-15.5	-25.1	-25.1	5.3
Total BHE Length (Increase), 2 x 100 m = 200 m	0.4	3.6	-4.5	-7.3	-7.3	8.0
Total BHE Length (Increase), 2 x 135 m = 270 m	4.7	16.2	-12.8	-20.8	-20.8	26.7
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	26.1	0.0	65.6	106.6	106.6	-51.9
Thermal Conductivity (Increase), Kf,s = 4.5 W/mK	-4.8	0.0	-12.1	-19.7	-19.7	24.9
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-6.2	0.0	-15.5	-25.4	-25.4	34.5

Appendix A: Supporting Documentation for Chapter 4

Table A.10 – Summary of Technical Parameter Sensitivity Analysis for Case 2: GHP + AE in Denver, CO.

	Sensitivity Analysis - Case 2: GHP+AE; Location: Denver, CO					
Technical Parameter	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 105 m = 210 m	43.6	26.1	17.5	160.1	133.2	4.5
Thermal Conductivity (Base Case), Kf,s = 2.4 W/mK	43.6	26.1	17.5	160.1	133.2	4.5
Air Economizer Setpoint (Base Case), Tae = 10°C	43.6	26.1	17.5	160.1	133.2	4.5
Air Economizer Setpoint (Decrease), Tae = 5°C	47.3	26.1	21.2	212.0	176.4	4.2
Air Economizer Setpoint (Increase), Tae = 15°C	40.4	26.1	14.4	116.1	96.5	4.7
Total BHE Length (Increase), 2 x 120 m = 240 m	44.1	27.5	16.6	146.5	121.9	4.9
Total BHE Length (Increase), 3 x 110 m = 330 m	47.1	31.9	15.3	128.7	107.1	5.6
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	53.2	26.1	27.1	294.1	244.6	2.4
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	41.7	26.1	15.6	133.6	111.1	5.4
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	40.5	26.1	14.4	117.0	97.3	6.1

	% Change from Base Case Estimates					
Technical Parameter	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 105 m = 210 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.4 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Base Case), Tae = 10°C	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Decrease), Tae = 5°C	8.5	0.0	21.3	32.4	32.4	-4.8
Air Economizer Setpoint (Increase), Tae = 15°C	-7.3	0.0	-18.1	-27.5	-27.5	5.7
Total BHE Length (Increase), 2 x 120 m = 240 m	1.1	5.5	-5.5	-8.5	-8.5	9.4
Total BHE Length (Increase), 3 x 110 m = 330 m	8.0	22.1	-12.9	-19.6	-19.6	24.7
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	21.9	0.0	54.6	83.7	83.7	-45.8
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	-4.3	0.0	-10.8	-16.6	-16.6	20.1
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	-7.1	0.0	-17.6	-26.9	-26.9	37.4

Table A.11 – Summary of Technical Parameter Sensitivity Analysis for Case 2: GHP + AE in Sacramento, CA.

	Sensitivity Analysis - Case 2: GHP+AE; Location: Sacramento, CA					
Technical Parameter	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 3 x 110 m = 330 m	62.4	31.9	30.6	231.8	68.7	4.4
Thermal Conductivity (Base Case), Kf,s = 2.5 W/mK	62.4	31.9	30.6	231.8	68.7	4.4
Air Economizer Setpoint (Base Case), Tae = 10°C	62.4	31.9	30.6	231.8	68.7	4.4
Air Economizer Setpoint (Decrease), Tae = 5°C	70.9	31.9	39.1	312.5	92.6	4.1
Air Economizer Setpoint (Increase), Tae = 15°C	52.3	31.9	20.5	136.2	40.4	4.9
Total BHE Length (Increase), 3 x 125 m = 375 m	63.2	34.0	29.2	218.2	64.7	4.7
Total BHE Length (Increase), 4 x 125 m = 500 m	67.3	40.0	27.3	200.1	59.3	5.1
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	77.9	31.9	46.0	381.2	113.0	2.7
Thermal Conductivity (Increase), Kf,s = 4.0 W/mK	59.0	31.9	27.1	198.6	58.8	5.1
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	57.3	31.9	25.4	182.4	54.0	5.6

	% Change from Base Case Estimates					
Technical Parameter	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 3 x 110 m = 330 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.5 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Base Case), Tae = 10°C	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Decrease), Tae = 5°C	13.6	0.0	27.8	34.8	34.8	-6.9
Air Economizer Setpoint (Increase), Tae = 15°C	-16.2	0.0	-33.1	-41.3	-41.3	10.7
Total BHE Length (Increase), 3 x 125 m = 375 m	1.2	6.8	-4.6	-5.8	-5.8	6.3
Total BHE Length (Increase), 4 x 125 m = 500 m	7.7	25.6	-10.9	-13.7	-13.7	15.9
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	24.7	0.0	50.5	64.5	64.5	-39.4
Thermal Conductivity (Increase), Kf,s = 4.0 W/mK	-5.5	0.0	-11.3	-14.3	-14.3	16.9
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-8.2	0.0	-16.8	-21.3	-21.3	27.3

Table A.12 – Summary of Technical Parameter Sensitivity Analysis for Case 2: GHP + AE in Miami, FL.

	Sensitivity Analysis - Case 2: GHP+AE; Location: Miami, FL					
Technical Parameter	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 8 x 135 m = 1080 m	100.7	68.9	31.8	359.4	184.4	3.9
Thermal Conductivity (Base Case), Kf,s = 2.1 W/mK	100.7	68.9	31.8	359.4	184.4	3.9
Air Economizer Setpoint (Base Case), Tae = 10°C	100.7	68.9	31.8	359.4	184.4	3.9
Air Economizer Setpoint (Decrease), Tae = 5°C	100.9	68.9	31.9	361.5	185.4	3.9
Air Economizer Setpoint (Increase), Tae = 15°C	99.5	68.9	30.6	342.4	175.7	3.9
Total BHE Length (Increase), 8 x 150 m = 1200 m	106.0	74.8	31.2	351.1	180.1	4.0
Total BHE Length (Increase), 10 x 150 m = 1500 m	119.9	89.5	30.3	338.5	173.6	4.1
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	105.8	68.9	36.9	433.6	222.4	3.2
Thermal Conductivity (Increase), Kf,s = 4.1 W/mK	98.0	68.9	29.1	320.4	164.4	4.3
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	97.2	68.9	28.3	308.4	158.2	4.5

	% Change from Base Case Estimates					
Technical Parameter	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 8 x 135 m = 1080 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.1 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Base Case), Tae = 10°C	0.0	0.0	0.0	0.0	0.0	0.0
Air Economizer Setpoint (Decrease), Tae = 5°C	0.2	0.0	0.5	0.6	0.6	-0.1
Air Economizer Setpoint (Increase), Tae = 15°C	-1.2	0.0	-3.8	-4.7	-4.7	0.9
Total BHE Length (Increase), 8 x 150 m = 1200 m	5.3	8.5	-1.8	-2.3	-2.3	2.4
Total BHE Length (Increase), 10 x 150 m = 1500 m	19.0	29.9	-4.6	-5.8	-5.8	6.2
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	5.1	0.0	16.1	20.6	20.6	-17.1
Thermal Conductivity (Increase), Kf,s = 4.1 W/mK	-2.7	0.0	-8.5	-10.8	-10.8	12.2
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-3.5	0.0	-11.1	-14.2	-14.2	16.5

Table A.13 – Summary of Technical Parameter Sensitivity Analysis for Case 3: GHP + DC in Varna, NY.

	Sensitivity Analysis - Case 3: GHP+DC; Location: Varna, NY					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 55 m = 110 m	58.5	21.8	36.7	365.7	68.1	4.4
Thermal Conductivity (Base Case), Kf,s = 2.2 W/mK	58.5	21.8	36.7	365.7	68.1	4.4
Total BHE Length (Increase), 2 x 65 m = 130 m	56.0	22.8	33.1	326.8	60.9	5.0
Total BHE Length (Increase), 2 x 85 m = 170 m	54.9	24.9	29.9	291.6	54.3	5.8
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	62.6	21.8	40.8	409.1	76.2	3.8
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	52.4	21.8	30.6	299.2	55.7	5.6
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	50.2	21.8	28.4	274.6	51.2	6.3

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 55 m = 110 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.2 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 65 m = 130 m	-4.3	4.8	-9.7	-10.7	-10.7	14.9
Total BHE Length (Increase), 2 x 85 m = 170 m	-6.2	14.5	-18.5	-20.3	-20.3	32.6
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	7.0	0.0	11.2	11.8	11.8	-12.6
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	-10.4	0.0	-16.5	-18.2	-18.2	28.3
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-14.2	0.0	-22.7	-24.9	-24.9	43.3

Table A.14 – Summary of Technical Parameter Sensitivity Analysis for Case 3: GHP + DC in Caribou, ME.

	Sensitivity Analysis - Case 3: GHP+DC; Location: Caribou, ME					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 35 m = 70 m	57.1	19.7	37.4	385.0	112.4	4.0
Thermal Conductivity (Base Case), Kf,s = 3.0 W/mK	57.1	19.7	37.4	385.0	112.4	4.0
Total BHE Length (Increase), 2 x 40 m = 80 m	55.0	20.2	34.7	355.9	103.9	4.4
Total BHE Length (Increase), 2 x 55 m = 110 m	49.9	21.8	28.1	280.7	81.9	5.9
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	59.0	19.7	39.4	406.0	118.5	3.8
Thermal Conductivity (Increase), Kf,s = 4.6 W/mK	50.8	19.7	31.1	314.9	91.9	5.1
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	47.8	19.7	28.1	280.6	81.9	5.9

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 35 m = 70 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 3.0 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 40 m = 80 m	-3.8	2.7	-7.2	-7.6	-7.6	9.9
Total BHE Length (Increase), 2 x 55 m = 110 m	-12.7	10.7	-25.0	-27.1	-27.1	47.5
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	3.4	0.0	5.1	5.4	5.4	-6.1
Thermal Conductivity (Increase), Kf,s = 4.6 W/mK	-11.0	0.0	-16.8	-18.2	-18.2	27.6
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	-16.3	0.0	-24.9	-27.1	-27.1	47.5

Table A.15 – Summary of Technical Parameter Sensitivity Analysis for Case 3: GHP + DC in Minneapolis, MN.

	Sensitivity Analysis - Case 3: GHP+DC; Location: Minneapolis, MN					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 55 m = 110 m	49.2	20.7	28.5	343.8	223.7	4.6
Thermal Conductivity (Base Case), Kf,s = 2.6 W/mK	49.2	20.7	28.5	343.8	223.7	4.6
Total BHE Length (Increase), 2 x 65 m = 130 m	47.3	21.5	25.8	307.2	199.9	5.3
Total BHE Length (Increase), 2 x 85 m = 170 m	46.5	23.2	23.3	273.2	177.8	6.2
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	55.0	20.7	34.4	421.4	274.2	3.6
Thermal Conductivity (Increase), Kf,s = 4.5 W/mK	44.6	20.7	23.9	281.7	183.3	5.9
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	43.3	20.7	22.7	264.4	172.1	6.4

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 55 m = 110 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.6 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 65 m = 130 m	-3.7	4.1	-9.4	-10.6	-10.6	14.8
Total BHE Length (Increase), 2 x 85 m = 170 m	-5.4	12.4	-18.2	-20.5	-20.5	33.0
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	11.9	0.0	20.6	22.6	22.6	-21.5
Thermal Conductivity (Increase), Kf,s = 4.5 W/mK	-9.3	0.0	-16.0	-18.1	-18.1	28.0
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-11.8	0.0	-20.4	-23.1	-23.1	38.7

Table A.16 – Summary of Technical Parameter Sensitivity Analysis for Case 3: GHP + DC in Denver, CO.

	Sensitivity Analysis - Case 3: GHP+DC; Location: Denver, CO					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 70 m = 140 m	49.4	22.7	26.6	326.4	271.4	5.1
Thermal Conductivity (Base Case), Kf,s = 2.4 W/mK	49.4	22.7	26.6	326.4	271.4	5.1
Total BHE Length (Increase), 2 x 80 m = 160 m	49.1	23.7	25.4	309.0	256.9	5.4
Total BHE Length (Increase), 2 x 105 m = 210 m	49.8	26.1	23.7	285.3	237.2	6.0
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	55.7	22.7	33.0	413.6	344.0	3.8
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	47.1	22.7	24.4	294.5	244.9	5.8
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	45.6	22.7	22.9	274.5	228.3	6.3

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 70 m = 140 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.4 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 80 m = 160 m	-0.6	4.2	-4.7	-5.3	-5.3	7.1
Total BHE Length (Increase), 2 x 105 m = 210 m	0.8	14.8	-11.1	-12.6	-12.6	18.5
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	12.9	0.0	23.9	26.7	26.7	-24.9
Thermal Conductivity (Increase), Kf,s = 3.7 W/mK	-4.6	0.0	-8.6	-9.8	-9.8	13.8
Thermal Conductivity (Increase), Kf,s = 6.6 W/mK	-7.5	0.0	-14.0	-15.9	-15.9	24.6

Table A.17 – Summary of Technical Parameter Sensitivity Analysis for Case 3: GHP + DC in Sacramento, CA.

	Sensitivity Analysis: Case 3: GHP+DC; Location: Sacramento, CA					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 2 x 120 m = 240 m	65.3	27.5	37.8	325.2	96.4	5.4
Thermal Conductivity (Base Case), Kf,s = 2.5 W/mK	65.3	27.5	37.8	325.2	96.4	5.4
Total BHE Length (Increase), 2 x 135 m = 270 m	66.5	29.0	37.5	322.1	95.4	5.5
Total BHE Length (Increase), 3 x 120 m = 360 m	70.2	33.3	36.9	317.1	94.0	5.6
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	68.0	27.5	40.5	350.6	103.9	4.9
Thermal Conductivity (Increase), Kf,s = 4.0 W/mK	64.6	27.5	37.1	318.5	94.4	5.5
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	64.3	27.5	36.7	314.9	93.3	5.6

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 2 x 120 m = 240 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.5 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 2 x 135 m = 270 m	1.7	5.2	-0.9	-1.0	-1.0	1.3
Total BHE Length (Increase), 3 x 120 m = 360 m	7.5	20.9	-2.3	-2.5	-2.5	3.4
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	4.1	0.0	7.1	7.8	7.8	-9.2
Thermal Conductivity (Increase), Kf,s = 4.0 W/mK	-1.1	0.0	-1.9	-2.1	-2.1	2.8
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-1.7	0.0	-2.9	-3.2	-3.2	4.3

Table A.18 – Summary of Technical Parameter Sensitivity Analysis for Case 3: GHP + DC in Miami, FL.

	Sensitivity Analysis - Case 3: GHP+DC; Location: Miami, FL					
Simulation	**TCO ($1,000)**	**CAP Cost ($1,000)**	**LOM Cost ($1,000)**	**LEC (MWhe)**	**LCO_2e (Tons)**	**Lifetime Average COP**
Total BHE Length (Base Case), 4 x 130 m = 520 m	78.5	41.5	37.0	468.9	240.5	3.7
Thermal Conductivity (Base Case), Kf,s = 2.1 W/mK	78.5	41.5	37.0	468.9	240.5	3.7
Total BHE Length (Increase), 4 x 145 m = 580 m	81.4	44.4	36.9	468.3	240.2	3.7
Total BHE Length (Increase), 6 x 130 m = 780 m	91.1	54.2	36.9	467.3	239.7	3.7
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	78.7	41.5	37.2	471.6	241.9	3.6
Thermal Conductivity (Increase), Kf,s = 4.1 W/mK	78.3	41.5	36.9	467.2	239.7	3.7
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	78.3	41.5	36.8	466.8	239.4	3.7

	% Change from Base Case Estimates					
Simulation	**TCO (%)**	**CAP Costs (%)**	**LOM Costs (%)**	**LEC (%)**	**LCO_2e (%)**	**Lifetime Average COP (%)**
Total BHE Length (Base Case), 4 x 130 m = 520 m	0.0	0.0	0.0	0.0	0.0	0.0
Thermal Conductivity (Base Case), Kf,s = 2.1 W/mK	0.0	0.0	0.0	0.0	0.0	0.0
Total BHE Length (Increase), 4 x 145 m = 580 m	3.7	7.1	-0.1	-0.1	-0.1	0.2
Total BHE Length (Increase), 6 x 130 m = 780 m	16.1	30.7	-0.3	-0.3	-0.3	0.4
Thermal Conductivity (Decrease), Kf,s = 1.2 W/mK	0.2	0.0	0.5	0.6	0.6	-0.7
Thermal Conductivity (Increase), Kf,s = 4.1 W/mK	-0.1	0.0	-0.3	-0.3	-0.3	0.4
Thermal Conductivity (Increase), Kf,s = 6.2 W/mK	-0.2	0.0	-0.4	-0.5	-0.5	0.6

Table A.19 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP – only in Varna, NY.

Sensitivity Analysis - Case 1: GHP - only; Location: Varna, NY										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP Equipment	56.3	60.3	61.3	62.3	66.3	-8.2	-1.6	0.0	1.6	8.2
Installation	58.8	60.8	61.3	61.8	63.8	-4.1	-0.8	0.0	0.8	4.1
Drilling	55.5	60.1	61.3	62.4	67.1	-9.4	-1.9	0.0	1.9	9.4
Operating	45.4	58.1	61.3	64.5	77.1	-25.9	-5.2	0.0	5.2	25.9
Maintenance	59.8	61.0	61.3	61.6	62.8	-2.4	-0.5	0.0	0.5	2.4
Incentives	48.0	58.6	61.3			-21.7	-4.3	0.0		

Table A.20 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP – only in Caribou, ME.

Sensitivity Analysis - Case 1: GHP - only; Location: Caribou, ME										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP Equipment	51.1	55.1	56.1	57.1	61.1	-8.9	-1.8	0.0	1.8	8.9
Installation	53.6	55.6	56.1	56.6	58.6	-4.5	-0.9	0.0	0.9	4.5
Drilling	52.7	55.4	56.1	56.8	59.5	-6.1	-1.2	0.0	1.2	6.1
Operating	40.4	53.0	56.1	59.2	71.7	-27.9	-5.6	0.0	5.6	27.9
Maintenance	54.6	55.8	56.1	56.4	57.6	-2.7	-0.5	0.0	0.5	2.7
Incentives	45.2	53.9	56.1			-19.5	-3.9	0.0		

Table A.21 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP – only in Minneapolis, MN.

Sensitivity Analysis - Case 1: GHP - only; Location: Minneapolis, MN										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
GHP Equipment	43.1	47.1	48.1	49.1	53.1	-10.4	-2.1	0.0	2.1	10.4
Installation	45.6	47.6	48.1	48.6	50.6	-5.2	-1.0	0.0	1.0	5.2
Drilling	43.4	47.2	48.1	49.1	52.8	-9.7	-1.9	0.0	1.9	9.7
Operating	37.7	46.0	48.1	50.2	58.5	-21.6	-4.3	0.0	4.3	21.6
Maintenance	46.6	47.8	48.1	48.4	49.6	-3.1	-0.6	0.0	0.6	3.1
Incentives	35.9	45.7	48.1			-25.3	-5.1	0.0		

Table A.22 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP – only in Denver, CO.

Sensitivity Analysis - Case 1: GHP - only; Location: Denver, CO										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
GHP Equipment	47.3	51.3	52.3	53.3	57.3	-9.6	-1.9	0.0	1.9	9.6
Installation	49.8	51.8	52.3	52.8	54.8	-4.8	-1.0	0.0	1.0	4.8
Drilling	45.8	51.0	52.3	53.6	58.8	-12.4	-2.5	0.0	2.5	12.4
Operating	41.6	50.1	52.3	54.4	62.9	-20.4	-4.1	0.0	4.1	20.4
Maintenance	50.8	52.0	52.3	52.6	53.8	-2.8	-0.6	0.0	0.6	2.8
Incentives	38.3	49.5	52.3			-26.8	-5.4	0.0		

Table A.23 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP – only in Sacramento, CA.

Sensitivity Analysis - Case 1: GHP - only; Location: Sacramento, CA										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
GHP Equipment	64.4	68.4	69.4	70.4	74.4	-7.2	-1.4	0.0	1.4	7.2
Installation	66.9	68.9	69.4	69.9	71.9	-3.6	-0.7	0.0	0.7	3.6
Drilling	60.7	67.6	69.4	71.1	78.0	-12.5	-2.5	0.0	2.5	12.5
Operating	52.3	66.0	69.4	72.8	86.4	-24.6	-4.9	0.0	4.9	24.6
Maintenance	67.9	69.1	69.4	69.7	70.9	-2.1	-0.4	0.0	0.4	2.1
Incentives	53.2	66.1	69.4			-23.3	-4.7	0.0		

Table A.24 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP – only in Miami, FL.

Sensitivity Analysis - Case 1: GHP - only; Location: Miami, FL										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
GHP Equipment	91.9	95.9	96.9	97.9	101.9	-5.2	-1.0	0.0	1.0	5.2
Installation	94.4	96.4	96.9	97.4	99.4	-2.6	-0.5	0.0	0.5	2.6
Drilling	70.4	91.6	96.9	102.2	123.4	-27.3	-5.5	0.0	5.5	27.3
Operating	83.9	94.3	96.9	99.5	109.9	-13.4	-2.7	0.0	2.7	13.4
Maintenance	95.4	96.6	96.9	97.2	98.4	-1.5	-0.3	0.0	0.3	1.5
Incentives	62.9	90.1	96.9			-35.1	-7.0	0.0		

Table A.25 – Summary of Financial Parameter Sensitivity Analysis for Case 2: GHP + AE in Varna, NY.

Sensitivity Analysis - Case 2: GHP + AE; Location: Varna, NY										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + AE Equipment	40.3	44.7	45.8	46.9	51.3	-12.0	-2.4	0.0	2.4	12.0
Installation	43.3	45.3	45.8	46.3	48.3	-5.5	-1.1	0.0	1.1	5.5
Drilling	41.1	44.9	45.8	46.7	50.5	-10.3	-2.1	0.0	2.1	10.3
Operating	38.6	44.4	45.8	47.2	53.0	-15.7	-3.1	0.0	3.1	15.7
Maintenance	42.8	45.2	45.8	46.4	48.8	-6.5	-1.3	0.0	1.3	6.5
Incentives	33.1	43.3	45.8			-27.8	-5.6	0.0		

Table A.26 – Summary of Financial Parameter Sensitivity Analysis for Case 2: GHP + AE in Caribou, ME.

Sensitivity Analysis - Case 2: GHP + AE; Location: Caribou, ME										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + AE Equipment	33.0	37.4	38.5	39.6	44.0	-14.3	-2.9	0.0	2.9	14.3
Installation	36.0	38.0	38.5	39.0	41.0	-6.5	-1.3	0.0	1.3	6.5
Drilling	35.9	38.0	38.5	39.0	41.1	-6.8	-1.4	0.0	1.4	6.8
Operating	32.9	37.4	38.5	39.6	44.2	-14.7	-2.9	0.0	2.9	14.7
Maintenance	35.5	37.9	38.5	39.1	41.5	-7.7	-1.5	0.0	1.5	7.7
Incentives	27.9	36.4	38.5			-27.6	-5.5	0.0		

Table A.27 – Summary of Financial Parameter Sensitivity Analysis for Case 2: GHP + AE in Minneapolis, MN.

Sensitivity Analysis - Case 2: GHP + AE; Location: Minneapolis, MN										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + AE Equipment	33.8	38.2	39.3	40.4	44.8	-14.0	-2.8	0.0	2.8	14.0
Installation	36.8	38.8	39.3	39.8	41.8	-6.4	-1.3	0.0	1.3	6.4
Drilling	35.5	38.6	39.3	40.1	43.2	-9.8	-2.0	0.0	2.0	9.8
Operating	34.5	38.4	39.3	40.3	44.2	-12.3	-2.5	0.0	2.5	12.3
Maintenance	36.3	38.7	39.3	39.9	42.3	-7.6	-1.5	0.0	1.5	7.6
Incentives	27.5	37.0	39.3			-30.1	-6.0	0.0		

Table A.28 – Summary of Financial Parameter Sensitivity Analysis for Case 2: GHP +AE in Denver, CO.

Sensitivity Analysis - Case 2: GHP + AE; Location: Denver, CO										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + AE Equipment	38.1	42.5	43.6	44.7	49.1	-12.6	-2.5	0.0	2.5	12.6
Installation	41.1	43.1	43.6	44.1	46.1	-5.7	-1.1	0.0	1.1	5.7
Drilling	38.6	42.6	43.6	44.6	48.7	-11.6	-2.3	0.0	2.3	11.6
Operating	37.8	42.5	43.6	44.8	49.4	-13.3	-2.7	0.0	2.7	13.3
Maintenance	40.6	43.0	43.6	44.2	46.6	-6.8	-1.4	0.0	1.4	6.8
Incentives	30.6	41.0	43.6			-29.9	-6.0	0.0		

Table A.29 – Summary of Financial Parameter Sensitivity Analysis for Case 2: GHP + AE in Sacramento, CA.

Sensitivity Analysis - Case 2: GHP + AE; Location: Sacramento, CA										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + AE Equipment	56.9	61.3	62.4	63.5	67.9	-8.8	-1.8	0.0	1.8	8.8
Installation	59.9	61.9	62.4	62.9	64.9	-4.0	-0.8	0.0	0.8	4.0
Drilling	54.5	60.9	62.4	64.0	70.4	-12.7	-2.5	0.0	2.5	12.7
Operating	50.1	60.0	62.4	64.9	74.8	-19.7	-3.9	0.0	3.9	19.7
Maintenance	59.5	61.8	62.4	63.0	65.4	-4.8	-1.0	0.0	1.0	4.8
Incentives	46.5	59.3	62.4			-25.5	-5.1	0.0		

Table A.30 – Summary of Financial Parameter Sensitivity Analysis for Case 2: GHP + AE in Miami, FL.

Sensitivity Analysis - Case 2: GHP + AE; Location: Miami, FL										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + AE Equipment	95.2	99.6	100.7	101.8	106.2	-5.5	-1.1	0.0	1.1	5.5
Installation	98.2	100.2	100.7	101.2	103.2	-2.5	-0.5	0.0	0.5	2.5
Drilling	74.3	95.4	100.7	106.0	127.2	-26.3	-5.3	0.0	5.3	26.3
Operating	87.8	98.1	100.7	103.3	113.7	-12.8	-2.6	0.0	2.6	12.8
Maintenance	97.8	100.1	100.7	101.3	103.7	-3.0	-0.6	0.0	0.6	3.0
Incentives	66.3	93.8	100.7			-34.2	-6.8	0.0		

Table A.31 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP + DC in Varna, NY.

Sensitivity Analysis - Case 3: GHP + DC; Location: Varna, NY										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
GHP + DC Equipment	53.0	57.4	58.5	59.6	64.0	-9.4	-1.9	0.0	1.9	9.4
Installation	56.0	58.0	58.5	59.0	61.0	-4.3	-0.9	0.0	0.9	4.3
Drilling	55.6	57.9	58.5	59.1	61.4	-4.9	-1.0	0.0	1.0	4.9
Operating	41.6	55.1	58.5	61.9	75.4	-28.8	-5.8	0.0	5.8	28.8
Maintenance	57.0	58.2	58.5	58.8	60.0	-2.5	-0.5	0.0	0.5	2.5
Incentives	47.6	56.3	58.5			-18.6	-3.7	0.0		

Table A.32 – Summary of Financial Parameter Sensitivity Analysis for Case 1: GHP + DC in Caribou, ME.

Sensitivity Analysis - Case 3: GHP + DC; Location: Caribou, ME										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
GHP + DC Equipment	51.6	56.0	57.1	58.2	62.6	-9.6	-1.9	0.0	1.9	9.6
Installation	54.6	56.6	57.1	57.6	59.6	-4.4	-0.9	0.0	0.9	4.4
Drilling	55.3	56.7	57.1	57.5	59.0	-3.2	-0.6	0.0	0.6	3.2
Operating	39.9	53.7	57.1	60.6	74.3	-30.2	-6.0	0.0	6.0	30.2
Maintenance	55.6	56.8	57.1	57.4	58.6	-2.6	-0.5	0.0	0.5	2.6
Incentives	47.3	55.1	57.1			-17.2	-3.4	0.0		

Table A.33 – Summary of Financial Parameter Sensitivity Analysis for Case 3: GHP + DC in Minneapolis, MN.

Sensitivity Analysis - Case 3: GHP + DC; Location: Minneapolis, MN										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
GHP + DC Equipment	43.7	48.1	49.2	50.3	54.7	-11.2	-2.2	0.0	2.2	11.2
Installation	46.7	48.7	49.2	49.7	51.7	-5.1	-1.0	0.0	1.0	5.1
Drilling	46.8	48.7	49.2	49.6	51.5	-4.8	-1.0	0.0	1.0	4.8
Operating	36.4	46.6	49.2	51.7	61.9	-25.9	-5.2	0.0	5.2	25.9
Maintenance	47.7	48.9	49.2	49.5	50.7	-3.0	-0.6	0.0	0.6	3.0
Incentives	38.8	47.1	49.2			-21.0	-4.2	0.0		

Table A.34 – Summary of Financial Parameter Sensitivity Analysis for Case 3: GHP +DC in Denver, CO.

Sensitivity Analysis - Case 3: GHP + DC; Location: Denver, CO										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + DC Equipment	43.9	48.3	49.4	50.5	54.9	-11.1	-2.2	0.0	2.2	11.1
Installation	46.9	48.9	49.4	49.9	51.9	-5.1	-1.0	0.0	1.0	5.1
Drilling	46.0	48.7	49.4	50.0	52.7	-6.8	-1.4	0.0	1.4	6.8
Operating	37.5	47.0	49.4	51.7	61.2	-24.0	-4.8	0.0	4.8	24.0
Maintenance	47.9	49.1	49.4	49.7	50.9	-3.0	-0.6	0.0	0.6	3.0
Incentives	38.0	47.1	49.4			-23.0	-4.6	0.0		

Table A.35 – Summary of Financial Parameter Sensitivity Analysis for Case 3: GHP + DC in Sacramento, CA.

Sensitivity Analysis - Case 3: GHP + DC; Location: Sacramento, CA										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + DC Equipment	59.8	64.2	65.3	66.4	70.8	-8.4	-1.7	0.0	1.7	8.4
Installation	62.8	64.8	65.3	65.8	67.8	-3.8	-0.8	0.0	0.8	3.8
Drilling	59.6	64.2	65.3	66.5	71.1	-8.8	-1.8	0.0	1.8	8.8
Operating	47.9	61.9	65.3	68.8	82.8	-26.7	-5.3	0.0	5.3	26.7
Maintenance	63.9	65.0	65.3	65.6	66.8	-2.3	-0.5	0.0	0.5	2.3
Incentives	51.6	62.6	65.3			-21.1	-4.2	0.0		

Table A.36 – Summary of Financial Parameter Sensitivity Analysis for Case 3: GHP + DC in Miami, FL.

Sensitivity Analysis - Case 3: GHP + DC; Location: Miami, FL										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
GHP + DC Equipment	73.0	77.4	78.5	79.6	84.0	-7.0	-1.4	0.0	1.4	7.0
Installation	76.0	78.0	78.5	79.0	81.0	-3.2	-0.6	0.0	0.6	3.2
Drilling	65.7	75.9	78.5	81.0	91.2	-16.2	-3.2	0.0	3.2	16.2
Operating	61.5	75.1	78.5	81.9	95.5	-21.7	-4.3	0.0	4.3	21.7
Maintenance	77.0	78.2	78.5	78.8	80.0	-1.9	-0.4	0.0	0.4	1.9
Incentives	57.7	74.3	78.5			-26.4	-5.3	0.0		

Table A.37 – Summary of Financial Parameter Sensitivity Analysis for Case 4: ASHP in Varna, NY.

Sensitivity Analysis - Case 4: ASHP; Location: Varna, NY										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
ASHP Equipment	50.3	53.8	54.7	55.5	59.0	-8.0	-1.6	0.0	1.6	8.0
Operating	36.0	50.9	54.7	58.4	73.3	-34.1	-6.8	0.0	6.8	34.1
Maintenance	50.4	53.8	54.7	55.5	59.0	-7.9	-1.6	0.0	1.6	7.9

Table A.38 – Summary of Financial Parameter Sensitivity Analysis for Case 4: ASHP in Caribou, ME.

Sensitivity Analysis - Case 4: ASHP; Location: Caribou, ME										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
ASHP Equipment	46.9	50.4	51.3	52.1	55.6	-8.5	-1.7	0.0	1.7	8.5
Operating	34.3	47.9	51.3	54.7	68.2	-33.1	-6.6	0.0	6.6	33.1
Maintenance	47.0	50.4	51.3	52.1	55.6	-8.4	-1.7	0.0	1.7	8.4

Table A.39 – Summary of Financial Parameter Sensitivity Analysis for Case 4: ASHP in Minneapolis, MN.

Sensitivity Analysis - Case 4: ASHP; Location: Minneapolis, MN										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
ASHP Equipment	42.8	46.3	47.1	48.0	51.5	-9.2	-1.8	0.0	1.8	9.2
Operating	32.2	44.2	47.1	50.1	62.0	-31.6	-6.3	0.0	6.3	31.6
Maintenance	42.8	46.3	47.1	48.0	51.5	-9.2	-1.8	0.0	1.8	9.2

Table A.40 – Summary of Financial Parameter Sensitivity Analysis for Case 4: ASHP in Denver, CO.

Sensitivity Analysis - Case 4: ASHP; Location: Denver, CO										
Financial Parameter	**TCO ($1,000) Sensitivity**					**% Change in TCO from Base Case Estimates**				
	-50	**-10**	**Base Case**	**+10**	**+50**	**-50**	**-10**	**Base Case**	**+10**	**+50**
ASHP Equipment	43.2	46.7	47.6	48.5	51.9	-9.2	-1.8	0.0	1.8	9.2
Operating	32.5	44.6	47.6	50.6	62.7	-31.8	-6.4	0.0	6.4	31.8
Maintenance	43.3	46.7	47.6	48.4	51.9	-9.1	-1.8	0.0	1.8	9.1

Table A.41 – Summary of Financial Parameter Sensitivity Analysis for Case 4: ASHP in Sacramento, CA.

Sensitivity Analysis - Case 4: ASHP; Location: Sacramento, CA										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
ASHP Equipment	60.3	63.7	64.6	65.5	69.0	-6.7	-1.3	0.0	1.3	6.7
Operating	41.0	59.9	64.6	69.3	88.2	-36.6	-7.3	0.0	7.3	36.6
Maintenance	60.3	63.7	64.6	65.5	68.9	-6.7	-1.3	0.0	1.3	6.7

Table A.42 – Summary of Financial Parameter Sensitivity Analysis for Case 4: ASHP in Miami, FL.

Sensitivity Analysis - Case 4: ASHP; Location: Miami, FL										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
ASHP Equipment	49.3	52.8	53.7	54.5	58.0	-8.1	-1.6	0.0	1.6	8.1
Operating	35.5	50.0	53.7	57.3	71.8	-33.8	-6.8	0.0	6.8	33.8
Maintenance	49.4	52.8	53.7	54.5	58.0	-8.0	-1.6	0.0	1.6	8.0

Table A.43 – Summary of Financial Parameter Sensitivity Analysis for Case 5: ASHP + AE in Varna, NY.

Sensitivity Analysis - Case 5: ASHP + AE; Location: Varna, NY										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
ASHP + AE Equipment	36.3	40.2	41.2	42.1	46.0	-11.8	-2.4	0.0	2.4	11.8
Operating	31.3	39.2	41.2	43.2	51.1	-24.1	-4.8	0.0	4.8	24.1
Maintenance	35.4	40.0	41.2	42.3	47.0	-14.1	-2.8	0.0	2.8	14.1

Table A.44 – Summary of Financial Parameter Sensitivity Analysis for Case 5: ASHP + AE in Caribou, ME.

Sensitivity Analysis - Case 5: ASHP + AE; Location: Caribou, ME										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
ASHP + AE Equipment	30.5	34.4	35.4	36.4	40.3	-13.7	-2.7	0.0	2.7	13.7
Operating	28.4	34.0	35.4	36.8	42.4	-19.9	-4.0	0.0	4.0	19.9
Maintenance	29.6	34.2	35.4	36.6	41.2	-16.4	-3.3	0.0	3.3	16.4

Table A.45 – Summary of Financial Parameter Sensitivity Analysis for Case 5: ASHP + AE in Minneapolis, MN.

Sensitivity Analysis - Case 5: ASHP + AE; Location: Minneapolis, MN										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
ASHP + AE Equipment	32.3	36.2	37.2	38.2	42.1	-13.1	-2.6	0.0	2.6	13.1
Operating	29.3	35.6	37.2	38.8	45.2	-21.3	-4.3	0.0	4.3	21.3
Maintenance	31.4	36.0	37.2	38.4	43.0	-15.6	-3.1	0.0	3.1	15.6

Table A.46 – Summary of Financial Parameter Sensitivity Analysis for Case 5: ASHP + AE in Sacramento, CA.

Sensitivity Analysis - Case 5: ASHP + AE; Location: Sacramento, CA										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
ASHP + AE Equipment	53.7	57.5	58.5	59.5	63.4	-8.3	-1.7	0.0	1.7	8.3
Operating	39.9	54.8	58.5	62.2	77.1	-31.8	-6.4	0.0	6.4	31.8
Maintenance	52.7	57.4	58.5	59.7	64.3	-9.9	-2.0	0.0	2.0	9.9

Table A.47 – Summary of Financial Parameter Sensitivity Analysis for Case 5: ASHP + AE in Miami, FL.

Sensitivity Analysis - Case 5: ASHP + AE; Location: Miami, FL										
Financial Parameter	TCO ($1,000) Sensitivity					% Change in TCO from Base Case Estimates				
	-50	-10	Base Case	+10	+50	-50	-10	Base Case	+10	+50
ASHP + AE Equipment	52.7	56.6	57.5	58.5	62.4	-8.4	-1.7	0.0	1.7	8.4
Operating	39.4	53.9	57.5	61.2	75.6	-31.5	-6.3	0.0	6.3	31.5
Maintenance	51.7	56.4	57.5	58.7	63.3	-10.1	-2.0	0.0	2.0	10.1

APPENDIX B

SUPPORTING DOCUMENTATION

CHAPTER 6: DEVELOPMENT OF THE GEODISTRICT ENERGY TOOL FOR SUSTAINABLE NEIGHBORHOOD DESIGN

Appendix B: Supporting Documentation for Chapter 6

Table B.1 - Vertical Borehole Ground Loop Resistance ($R_B + R_G \cdot F_H$ for heating or $R_B + R_G \cdot F_C$ for cooling) for 3/4 –inch Nominal U-bend (hr·ft·°F/Btu) (reproduced from IGSHPA (2009) and adapted for the Model Assumptions on Table 4.11).

		Borehole Diameter = 5.00 in.								
F_H or F_C	K_G (Btu/hr·ft·°F)	K_{GROUT} (Btu/hr·ft·°F) 0.40	0.57	0.69	0.79	0.88	1.00	1.07	1.14	1.20
0.60	**0.70**	0.824	0.745	0.713	0.693	0.680	0.665	0.658	0.652	0.648
	0.85	0.738	0.659	0.627	0.607	0.593	0.579	0.572	0.566	0.561
	1.00	0.677	0.598	0.566	0.547	0.533	0.519	0.512	0.506	0.501
	1.15	0.633	0.554	0.522	0.502	0.488	0.474	0.467	0.461	0.456
	1.30	0.598	0.520	0.487	0.468	0.454	0.440	0.433	0.427	0.422
	1.60	0.549	0.470	0.438	0.418	0.405	0.390	0.383	0.377	0.373
	1.90	0.515	0.436	0.404	0.385	0.371	0.357	0.350	0.344	0.339
	2.20	0.491	0.412	0.380	0.360	0.346	0.332	0.325	0.319	0.314

Table B.2 - Submittal data for ClimateMaster TMW840 Large Series (60Hz I-P, HFC-410A) for a range of operating temperatures in cooling mode (ClimateMaster, 2015; 2016).

Source PD				LOAD																								
EWT °F	Flow			EWT °F	Flow 105 GPM							SLWT °F	Flow 158 GPM							SLWT °F	Flow 210 GPM							SLWT °F
	GPM	WPD			TC	kW	HR	LLWT	EER	WPD			TC	kW	HR	LLWT	EER	WPD			TC	kW	HR	LLWT	EER	WPD		
		PSI	FT							PSI	FT							PSI	FT							PSI	FT	
60	105	2.8	6.4	40	666.2	39.3	800.0	27.4	17.0	2.6	5.9	75.2	693.4	39.7	828.6	31.3	17.5	5.5	12.8	75.7	706.6	39.9	842.4	33.3	17.7	9.6	22.2	76.0
				50	783.4	41.1	923.2	35.2	19.1	2.6	5.9	77.5	821.0	41.7	962.8	39.6	19.7	5.5	12.8	78.3	839.2	42.0	982.0	42.1	20.0	9.6	22.2	78.7
				60	908.7	43.1	1055.5	42.8	21.1	2.6	5.9	80.1	959.1	44.0	1108.8	47.9	21.8	5.5	12.8	81.2	983.6	44.4	1134.8	50.7	22.2	9.6	22.2	81.7
				70	1040.7	45.4	1195.4	50.2	22.9	2.6	5.9	82.8	1106.4	46.6	1265.3	56.0	23.7	5.5	12.8	84.2	1138.5	47.3	1299.5	59.2	24.1	9.6	22.2	84.9
				80	1172.1	47.9	1335.3	57.7	24.5	2.6	5.9	85.6	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	158	6.0	13.8	70	1066.6	43.2	1213.7	49.7	24.7	2.6	5.9	75.4	1138.6	44.3	1289.6	55.6	25.7	5.5	12.8	76.4	1174.2	44.9	1327.2	58.8	26.1	9.6	22.2	76.9
				80	1210.5	45.5	1365.6	56.9	26.6	2.6	5.9	77.4	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
75	105	2.8	6.4	30	521.0	44.1	671.1	20.2	11.8	2.6	5.9	87.8	537.3	44.3	688.3	23.3	12.1	5.5	12.8	88.1	545.2	44.4	696.6	24.9	12.3	9.6	22.2	88.3
				40	622.6	45.6	778.0	28.3	13.7	2.6	5.9	89.8	645.8	46.0	802.4	31.9	14.0	5.5	12.8	90.3	657.0	46.1	814.2	33.8	14.2	9.6	22.2	90.5
				50	733.2	47.4	894.5	36.1	15.5	2.6	5.9	92.1	765.2	47.9	928.3	40.3	16.0	5.5	12.8	92.7	780.6	48.1	944.6	42.6	16.2	9.6	22.2	93.1
				60	851.6	49.4	1019.7	43.9	17.3	2.6	5.9	94.5	894.4	50.1	1065.2	48.7	17.8	5.5	12.8	95.4	915.1	50.5	1087.2	51.3	18.1	9.6	22.2	95.8
				70	976.3	51.7	1152.4	51.4	18.9	2.6	5.9	97.1	1032.2	52.8	1212.0	56.9	19.6	5.5	12.8	98.3	1059.2	53.4	1241.0	59.9	19.9	9.6	22.2	98.9
				80	1080.3	53.8	1263.5	59.4	20.1	2.6	5.9	99.3	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	158	6.0	13.8	30	530.7	42.4	675.1	20.0	12.5	2.6	5.9	83.5	548.0	42.6	693.1	23.1	12.9	5.5	12.8	83.8	556.3	42.7	701.8	24.8	13.0	9.6	22.2	83.9
				40	635.6	43.7	784.3	28.0	14.6	2.6	5.9	85.0	660.3	44.0	810.1	31.7	15.0	5.5	12.8	85.3	672.3	44.1	822.6	33.7	15.2	9.6	22.2	85.5
				50	750.2	45.1	904.0	35.8	16.6	2.6	5.9	86.5	784.8	45.6	940.1	40.1	17.2	5.5	12.8	87.0	801.5	45.8	957.6	42.4	17.5	9.6	22.2	87.2
				60	873.6	46.8	1033.1	43.4	18.7	2.6	5.9	88.2	920.4	47.5	1082.3	48.4	19.4	5.5	12.8	88.8	943.2	47.9	1106.3	51.1	19.7	9.6	22.2	89.1
				70	1004.4	48.8	1170.7	50.9	20.6	2.6	5.9	90.0	1066.1	49.8	1235.9	56.5	21.4	5.5	12.8	90.8	1096.3	50.4	1267.9	59.6	21.8	9.6	22.2	91.2
				80	1124.0	50.8	1297.1	58.6	22.1	2.6	5.9	91.6	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	210	10.4	24.1	30	535.5	41.6	677.1	19.9	12.9	2.6	5.9	81.4	553.2	41.8	695.5	23.1	13.2	5.5	12.8	81.6	561.8	41.9	704.4	24.7	13.4	9.6	22.2	81.7
				40	641.9	42.7	787.5	27.9	15.0	2.6	5.9	82.5	667.5	43.0	814.0	31.6	15.5	5.5	12.8	82.8	679.9	43.2	826.9	33.6	15.7	9.6	22.2	82.9
				50	758.6	44.1	908.7	35.7	17.2	2.6	5.9	83.7	794.5	44.5	946.1	40.0	17.8	5.5	12.8	84.0	811.9	44.7	964.2	42.3	18.2	9.6	22.2	84.2
				60	884.5	45.6	1039.9	43.2	19.4	2.6	5.9	84.9	933.4	46.3	1091.0	48.2	20.2	5.5	12.8	85.4	957.2	46.6	1116.0	50.9	20.5	9.6	22.2	85.7
				70	1018.2	47.5	1180.0	50.6	21.4	2.6	5.9	86.3	1083.1	48.5	1248.1	56.3	22.4	5.5	12.8	87.0	1115.0	48.9	1281.7	59.4	22.8	9.6	22.2	87.3
				80	1146.3	49.4	1314.7	58.2	23.2	2.6	5.9	87.6	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
90	105	2.8	6.4	30	477.5	51.9	654.4	21.0	9.2	2.6	5.9	102.5	491.1	52.2	668.8	23.8	9.4	5.5	12.8	102.8	679.9	43.2	826.9	33.6	15.7	9.6	22.2	82.9
				40	573.0	53.5	755.2	29.2	10.7	2.6	5.9	104.5	592.3	53.8	775.6	32.6	11.0	5.5	12.8	104.9	601.6	54.0	785.4	34.3	11.1	9.6	22.2	105.0
				50	676.9	55.2	865.1	37.2	12.3	2.6	5.9	106.6	703.5	55.7	893.4	41.1	12.6	5.5	12.8	107.1	716.2	56.0	906.9	43.2	12.8	9.6	22.2	107.4
				60	791.8	57.3	987.1	45.0	13.8	2.6	5.9	109.0	827.8	58.0	1025.5	49.5	14.3	5.5	12.8	109.7	845.0	58.4	1043.9	52.0	14.5	9.6	22.2	110.1
				70	909.4	59.7	1112.9	52.7	15.2	2.6	5.9	111.4	956.3	60.7	1163.3	57.9	15.7	5.5	12.8	112.4	975.2	61.2	1183.7	60.7	15.9	9.6	22.2	112.9
				80	989.2	61.5	1198.7	61.1	16.1	2.6	5.9	113.2	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	158	6.0	13.8	30	488.3	49.9	658.4	20.8	9.8	2.6	5.9	98.4	502.8	50.1	673.5	23.7	10.0	5.5	12.8	98.6	509.8	50.2	680.8	25.2	10.2	9.6	22.2	98.7
				40	587.2	51.2	761.5	28.9	11.5	2.6	5.9	99.7	608.0	51.4	783.2	32.4	11.8	5.5	12.8	100.0	618.0	51.6	793.6	34.2	12.0	9.6	22.2	100.1
				50	695.3	52.6	874.4	36.9	13.2	2.6	5.9	101.2	724.3	53.0	904.8	40.9	13.7	5.5	12.8	101.6	738.3	53.2	919.4	43.0	13.9	9.6	22.2	101.8
				60	811.7	54.2	996.4	44.6	15.0	2.6	5.9	102.8	851.0	54.8	1037.8	49.2	15.5	5.5	12.8	103.3	869.9	55.1	1057.8	51.7	15.8	9.6	22.2	103.6
				70	935.1	56.2	1126.5	52.2	16.6	2.6	5.9	104.5	987.0	57.1	1181.5	57.5	17.3	5.5	12.8	105.2	1011.5	57.5	1207.5	60.4	17.6	9.6	22.2	105.5
				80	1027.2	57.8	1224.2	60.4	17.8	2.6	5.9	105.7	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	210	10.4	24.1	30	493.6	49.0	660.4	20.7	10.1	2.6	5.9	96.3	508.6	49.1	675.9	23.6	10.4	5.5	12.8	96.5	515.8	49.2	683.4	25.1	10.5	9.6	22.2	96.5
				40	594.2	50.0	764.6	28.8	11.9	2.6	5.9	97.3	615.8	50.3	787.0	32.3	12.2	5.5	12.8	97.5	626.2	50.4	797.8	34.1	12.4	9.6	22.2	97.6
				50	704.5	51.3	879.1	36.7	13.7	2.6	5.9	98.4	734.7	51.6	910.6	40.7	14.2	5.5	12.8	98.7	749.3	51.8	925.8	42.9	14.5	9.6	22.2	98.9
				60	823.4	52.8	1003.1	44.4	15.6	2.6	5.9	99.6	864.6	53.3	1046.2	49.1	16.2	5.5	12.8	100.1	884.6	53.6	1067.1	51.6	16.5	9.6	22.2	100.3
				70	950.0	54.5	1135.7	51.9	17.4	2.6	5.9	100.9	1004.7	55.4	1193.3	57.3	18.2	5.5	12.8	101.5	1031.4	55.8	1221.4	60.2	18.5	9.6	22.2	101.8
				80	1049.5	56.1	1240.5	60.0	18.7	2.6	5.9	102.0	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
105	105	2.8	6.4	30	431.3	61.5	640.7	21.9	7.0	2.6	5.9	117.3	442.4	61.7	652.5	24.5	7.2	5.5	12.8	117.5	447.7	61.8	658.2	25.8	7.2	9.6	22.2	117.6
				40	520.8	63.1	735.9	30.2	8.3	2.6	5.9	119.1	536.6	63.4	752.7	33.3	8.5	5.5	12.8	119.5	544.1	63.6	760.7	34.9	8.6	9.6	22.2	119.6
				50	617.9	65.0	839.3	38.3	9.5	2.6	5.9	121.2	639.6	65.4	862.5	41.9	9.8	5.5	12.8	121.6	650.0	65.6	873.6	43.8	9.9	9.6	22.2	121.8
				60	721.7	67.1	950.4	46.3	10.8	2.6	5.9	123.3	750.7	67.8	981.6	50.5	11.1	5.5	12.8	124.0	764.5	68.1	996.5	52.7	11.2	9.6	22.2	124.3
				70	831.0	69.6	1068.2	54.2	11.9	2.6	5.9	125.7	868.7	70.5	1109.1	59.0	12.3	5.5	12.8	126.5	876.1	70.7	1117.1	61.7	12.4	9.6	22.2	126.6
	158	6.0	13.8	30	443.0	59.1	644.4	21.7	7.5	2.6	5.9	113.2	455.0	59.3	656.9	24.3	7.7	5.5	12.8	113.4	460.8	59.3	663.0	25.7	7.8	9.6	22.2	113.5
				40	536.2	60.4	741.8	29.9	8.9	2.6	5.9	114.5	553.3	60.6	759.8	33.0	9.1	5.5	12.8	114.7	561.6	60.7	768.4	34.7	9.3	9.6	22.2	114.8
				50	637.8	61.8	848.3	37.9	10.3	2.6	5.9	115.9	661.7	62.1	873.5	41.7	10.6	5.5	12.8	116.2	673.2	62.3	885.5	43.6	10.8	9.6	22.2	116.4
				60	747.1	63.5	963.3	45.8	11.8	2.6	5.9	117.4	779.5	64.0	997.6	50.1	12.2	5.5	12.8	117.8	795.1	64.3	1014.1	52.5	12.4	9.6	22.2	118.1
				70	863.1	65.4	1086.1	53.6	13.2	2.6	5.9	119.0	905.9	66.2	1131.7	58.5	13.7	5.5	12.8	119.6	918.4	66.5	1145.0	61.3	13.8	9.6	22.2	119.8
				80	931.1	66.7	1158.6	62.2	13.9	2.6	5.9	120.0	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	210	10.4	24.1	30	448.9	57.9	646.3	21.6	7.7	2.6	5.9	111.2	461.3	58.1	659.2	24.2	7.9	5.5	12.8	111.3	467.2	58.2	665.4	25.6	8.0	9.6	22.2	111.4
				40	543.8	59.0	744.8	29.7	9.2	2.6	5.9	112.2	561.7	59.2	763.4	32.9	9.5	5.5	12.8	112.3	570.3	59.3	772.4	34.6	9.6	9.6	22.2	112.4
				50	647.6	60.2	852.9	37.8	10.8	2.6	5.9	113.2	672.7	60.6	879.0	41.5	11.1	5.5	12.8	113.5	684.8	60.7	891.6	43.5	11.3	9.6	22.2	113.6
				60	759.7	61.7	969.9	45.6	12.3	2.6	5.9	114.3	793.9	62.2	1005.8	50.0	12.8	5.5	12.8	114.7	810.3	62.4	1023.1	52.3	13.0	9.6	22.2	114.9
				70	878.9	63.4	1095.1	53.3	13.9	2.6	5.9	115.6	905.9	66.2	1131.7	58.5	13.7	5.5	12.8	119.6	939.8	64.4	1159.4	61.1	14.6	9.6	22.2	116.2
120	105	2.8	6.4	30	377.2	72.8	625.4	22.9	5.2	2.6	5.9	132.1	385.8	73.0	634.6	25.2	5.3	5.5	12.8	132.2	389.9	73.1	639.0	26.3	5.3	9.6	22.2	132.3
				40	459.3	74.6	713.6	31.3	6.2	2.6	5.9	133.8	471.4	74.9	726.6	34.1	6.3	5.5	12.8	134.0	477.2	75.0	732.8	35.5	6.4	9.6	22.2	134.2
				50	548.0	76.6	809.1	39.6	7.2	2.6	5.9	135.6	564.7	77.0	827.1	42.9	7.3	5.5	12.8	136.0	572.6	77.2	835.6	44.6	7.4	9.6	22.2	136.2
				60	642.6	78.9	911.4	47.8	8.1	2.6	5.9	137.7	664.7	79.4	935.5	51.6	8.4	5.5	12.8	138.1	675.2	79.7	946.9	53.6	8.5	9.6	22.2	138.4
				70	741.9	81.5	1019.7	55.9	9.1	2.6	5.9	139.8	770.5	82.3	1051.2	60.2	9.4	5.5	12.8	140.4	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	158	6.0	13.8	30	390.1	70.1	628.9	22.7	5.6	2.6	5.9	128.1	399.4	70.2	638.7	25.0	5.7	5.5	12.8	128.2	403.9	70.3	643.4	26.2	5.7	9.6	22.2	128.3
				40	476.2	71.4	719.5	31.0	6.7	2.6	5.9	129.3	489.6	71.6	733.7	33.8	6.8	5.5	12.8	129.4	496.0	71.7	740.4	35.3	6.9	9.6	22.2	129.5
				50	569.9	72.9	818.4	39.2	7.8	2.6	5.9	130.5	588.6	73.2	838.2	42.6	8.0	5.5	12.8	130.8	597.5	73.4	847.6	44.3	8.1	9.6	22.2	130.9
				60	670.6	74.7	925.1	47.3	9.0	2.6	5.9	131.9	695.9	75.1	952.0	51.2	9.3	5.5	12.8	132.3	708.0	75.4	964.9	53.3	9.4	9.6	22.2	132.5
				70	777.4	76.7	1038.9	55.2	10.1	2.6	5.9	133.4	810.8	77.4	1074.8	59.7	10.5	5.5	12.8	133.9	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	210	10.4	24.1	30	396.5	68.7	630.6	22.5	5.8	2.6	5.9	126.1	406.2	68.8	640.8	24.9	5.9	5.5	12.8	126.2	410.9	68.9	645.7	26.1	6.0	9.6	22.2	126.2
				40	484.5	69.8	722.5	30.9	6.9	2.6	5.9	127.0	498.6	70.0	737.2	33.7	7.1	5.5	12.8	127.1	505.3	70.1	744.2	35.2	7.2	9.6	22.2	127.2
				50	580.6	71.1	823.0	39.0	8.2	2.6	5.9	128.0	600.4	71.4	843.7	42.4	8.4	5.5	12.8	128.2	609.9	71.5	853.6	44.2	8.5	9.6	22.2	128.3
				60	684.3	72.6	931.8	47.0	9.4	2.6	5.9	129.0	711.3	73.0	960.3	51.0	9.7	5.5	12.8	129.3	724.2	73.2	973.9	53.1	9.9	9.6	22.2	129.4
				70	794.8	74.4	1048.4	54.9	10.7	2.6	5.9	130.2	810.8	77.4	1074.8	59.7	10.5	5.5	12.8	133.9	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table B.2 Continued - Submittal data for ClimateMaster TMW840 Large Series (60Hz I-P, HFC-410A) for a range of operating temperatures in heating mode (ClimateMaster, 2015; 2016).

Source				LOAD																								
EWT °F	Flow			EWT °F	Flow 105 GPM							SLWT °F	Flow 158 GPM							SLWT °F	Flow 210 GPM							SLWT °F
	GPM	WPD			TC	kW	HE	LLWT	COP	WPD			TC	kW	HE	LLWT	COP	WPD			TC	kW	HE	LLWT	COP	GPM		
		PSI	FT							PSI	FT							PSI	FT							PSI	FT	
30	105	2.5	5.9	80	665.6	46.5	507.1	92.7	4.2	2.8	6.4	20.5	669.6	44.8	517.2	88.5	4.4	6.0	13.8	20.3	671.6	43.9	522.2	86.4	4.5	10.4	24.1	20.2
				100	646.0	58.1	448.0	112.4	3.3	2.8	6.4	21.6	649.8	55.9	459.5	108.3	3.4	6.0	13.8	21.4	649.2	54.8	462.6	106.2	3.5	10.4	24.1	21.3
	158	5.5	12.8	80	681.8	46.8	522.5	93.0	4.3	2.8	6.4	23.4	686.6	44.9	533.5	88.7	4.5	6.0	13.8	23.3	689.0	44.1	539.0	86.6	4.6	10.4	24.1	23.2
				100	658.7	58.3	460.0	112.6	3.3	2.8	6.4	24.2	663.2	56.0	472.3	108.5	3.5	6.0	13.8	24.1	662.8	54.9	475.8	106.3	3.5	10.4	24.1	24.0
				120	634.6	73.0	385.8	132.2	2.6	2.8	6.4	25.2	638.7	70.2	399.4	128.2	2.7	6.0	13.8	25.0	640.8	68.8	406.2	126.2	2.7	10.4	24.1	24.9
				130									626.7	78.6	358.8	138.1	2.3	6.0	13.8	25.5	628.8	77.1	366.1	136.1	2.4	10.4	24.1	25.4
	210	9.6	22.2	60	716.7	38.1	586.9	73.6	5.5	2.8	6.4	24.5	721.5	36.7	596.6	69.1	5.8	6.0	13.8	24.4	723.9	36.0	601.3	66.8	5.9	10.4	24.1	24.3
				80	689.6	46.9	529.9	93.1	4.3	2.8	6.4	25.0	694.8	45.0	541.4	88.8	4.5	6.0	13.8	24.9	697.4	44.2	547.1	86.6	4.6	10.4	24.1	24.9
				100	664.8	58.4	465.8	112.7	3.3	2.8	6.4	25.6	669.7	56.1	478.5	108.6	3.5	6.0	13.8	25.5	669.4	55.0	482.1	106.4	3.6	10.4	24.1	25.5
				120	639.0	73.1	389.9	132.3	2.6	2.8	6.4	26.3	643.4	70.3	403.9	128.3	2.7	6.0	13.8	26.2	645.7	68.9	410.9	126.2	2.8	10.4	24.1	26.1
				130									630.6	78.6	362.5	138.1	2.4	6.0	13.8	26.6	632.8	77.1	369.9	136.1	2.4	10.4	24.1	26.5
40	105	2.5	5.9	60	799.9	39.3	666.2	75.2	6.0	2.8	6.4	27.4	805.9	37.7	677.5	70.2	6.3	6.0	13.8	27.2	808.9	37.0	683.0	67.7	6.4	10.4	24.1	27.1
				80	770.4	48.1	606.7	94.7	4.7	2.8	6.4	28.6	776.7	46.0	620.1	89.9	5.0	6.0	13.8	28.3	779.9	45.0	626.7	87.4	5.1	10.4	24.1	28.2
				100	743.2	59.7	539.8	114.3	3.7	2.8	6.4	29.8	749.3	57.1	554.7	109.6	3.8	6.0	13.8	29.5	752.3	55.8	562.1	107.2	4.0	10.4	24.1	29.4
				120	713.5	74.6	459.3	133.8	2.8	2.8	6.4	31.3	719.5	71.4	476.1	129.3	3.0	6.0	13.8	31.0	722.4	69.8	484.4	127.0	3.0	10.4	24.1	30.9
				130									703.9	79.9	431.6	139.1	2.6	6.0	13.8	31.9	707.0	78.2	440.6	136.8	2.7	10.4	24.1	31.7
	158	5.5	12.8	60	828.6	39.7	693.4	75.7	6.1	2.8	6.4	31.3	836.0	38.1	706.4	70.6	6.4	6.0	13.8	31.1	839.7	37.3	712.7	68.0	6.6	10.4	24.1	31.0
				80	793.5	48.4	628.6	95.2	4.8	2.8	6.4	32.1	801.2	46.3	643.5	90.2	5.1	6.0	13.8	31.9	805.1	45.3	650.9	87.7	5.2	10.4	24.1	31.8
				100	761.3	60.0	556.8	114.6	3.7	2.8	6.4	33.0	768.6	57.3	573.2	109.8	3.9	6.0	13.8	32.8	772.3	56.0	581.3	107.4	4.0	10.4	24.1	32.7
				120	726.6	74.9	471.4	134.0	2.8	2.8	6.4	34.1	733.6	71.6	489.6	129.4	3.0	6.0	13.8	33.8	737.2	70.0	498.5	127.1	3.1	10.4	24.1	33.7
				130									715.5	80.1	442.6	139.2	2.6	6.0	13.8	34.4	719.2	78.3	452.2	137.0	2.7	10.4	24.1	34.3
	210	9.6	22.2	60	842.4	39.9	706.6	76.0	6.2	2.8	6.4	33.3	850.6	38.3	720.3	70.8	6.5	6.0	13.8	33.2	854.7	37.5	727.1	68.1	6.7	10.4	24.1	33.1
				80	804.6	48.6	639.1	95.4	4.9	2.8	6.4	34.0	813.0	46.4	654.8	90.3	5.1	6.0	13.8	33.8	817.2	45.4	662.6	87.8	5.3	10.4	24.1	33.7
				100	769.9	60.2	564.9	114.8	3.8	2.8	6.4	34.7	777.8	57.5	582.1	110.0	4.0	6.0	13.8	34.5	781.9	56.1	590.6	107.5	4.1	10.4	24.1	34.4
				120	732.8	75.0	477.2	134.2	2.9	2.8	6.4	35.5	740.4	71.7	496.0	129.5	3.0	6.0	13.8	35.3	744.2	70.1	505.3	127.2	3.1	10.4	24.1	35.2
				130									721.1	80.2	447.9	139.3	2.6	6.0	13.8	35.8	725.1	78.4	457.8	137.0	2.7	10.4	24.1	35.7
50	105	2.5	5.9	60	923.2	41.1	783.4	77.5	6.6	2.8	6.4	35.2	932.5	39.3	798.7	71.8	7.0	6.0	13.8	34.9	937.0	38.5	806.1	68.9	7.1	10.4	24.1	34.8
				80	884.7	49.8	715.1	96.9	5.2	2.8	6.4	36.5	894.2	47.4	732.6	91.4	5.5	6.0	13.8	36.1	898.9	46.3	741.3	88.6	5.7	10.4	24.1	36.0
				100	849.0	61.5	639.4	116.3	4.0	2.8	6.4	37.9	858.1	58.5	658.7	111.0	4.3	6.0	13.8	37.5	862.7	57.0	668.3	108.3	4.4	10.4	24.1	37.4
				120	809.0	76.6	548.0	135.6	3.1	2.8	6.4	39.6	818.3	72.9	569.8	130.5	3.3	6.0	13.8	39.2	823.0	71.1	580.6	128.0	3.4	10.4	24.1	39.0
				130									796.8	81.5	519.1	140.3	2.9				801.7	79.5	530.7	137.8	3.0	10.4	24.1	40.0
	158	5.5	12.8	60	962.8	41.7	821.0	78.3	6.8	2.8	6.4	39.6	974.6	39.9	838.9	72.4	7.2				980.4	39.0	847.7	69.3	7.4			
				80	916.6	50.3	745.3	97.5	5.3	2.8	6.4	40.6	928.4	47.9	765.3	91.8	5.7	6.0	13.8	40.3	934.3	46.7	775.2	88.9	5.9	10.4	24.1	40.2
				100	874.0	62.0	662.8	116.8	4.1	2.8	6.4	41.6	885.1	58.9	684.5	111.3	4.4	6.0	13.8	41.4	890.7	57.4	695.2	108.6	4.6	10.4	24.1	41.2
				120	827.0	77.0	564.7	136.0	3.2	2.8	6.4	42.9	838.2	73.2	588.6	130.8	3.4	6.0	13.8	42.6	843.7	71.4	600.4	128.2	3.5	10.4	24.1	42.4
				130	801.1	85.8	508.5	145.5	2.7	2.8	6.4	43.6	813.0	81.8	534.3	140.5	2.9				818.9	79.8	547.0	137.9	3.0	10.4	24.1	43.1
	210	9.6	22.2	60	982.0	42.0	839.2	78.7	6.9	2.8	6.4	42.1	995.1	40.1	858.5	72.6	7.3				1001.6	39.3	868.0	69.5	7.5			
				80	932.0	50.6	759.8	97.8	5.4	2.8	6.4	42.8	944.9	48.1	781.1	92.1	5.8	6.0	13.8	42.6	951.4	46.9	791.7	89.1	5.9	10.4	24.1	42.5
				100	886.0	62.2	674.0	117.1	4.2	2.8	6.4	43.6	898.1	59.1	696.8	111.5	4.5	6.0	13.8	43.4	904.2	57.5	708.2	108.7	4.6	10.4	24.1	43.3
				120	835.6	77.2	572.6	136.2	3.2	2.8	6.4	44.6	847.6	73.4	597.5	130.9	3.4	6.0	13.8	44.3	853.6	71.5	609.9	128.3	3.5	10.4	24.1	44.2
				130	808.0	86.0	514.9	145.7	2.8	2.8	6.4	45.1	820.8	81.9	541.6	140.6	2.9				827.1	79.9	554.8	138.0	3.0	10.4	24.1	44.7
60	105	2.5	5.9	60	1055.5	43.1	908.7	80.1	7.2	2.8	6.4	42.8	1068.8	41.1	928.9	73.6	7.6				1075.5	40.2	938.7	70.2	7.8			
				80	1007.5	51.8	831.1	99.3	5.7	2.8	6.4	44.2	1020.9	49.1	853.7	93.0	6.1	6.0	13.8	43.8	1027.7	47.8	864.9	89.8	6.3	10.4	24.1	43.6
				100	962.7	63.6	745.8	118.6	4.4	2.8	6.4	45.8	975.7	60.2	770.6	112.5	4.8	6.0	13.8	45.4	982.2	58.5	782.9	109.5	4.9	10.4	24.1	45.2
				120	911.3	78.9	642.5	137.7	3.4	2.8	6.4	47.8	925.0	74.7	670.5	131.9	3.6	6.0	13.8	47.3	931.8	72.6	684.3	129.0	3.8	10.4	24.1	47.0
				130	881.6	87.8	582.1	147.1	2.9	2.8	6.4	48.9	896.8	83.3	612.8	141.6	3.2				904.1	81.1	627.8	138.8	3.3	10.4	24.1	48.1
	158	5.5	12.8	60	1108.8	44.0	959.1	81.2	7.4	2.8	6.4	47.9	1126.1	41.9	983.4	74.3	7.9				1134.9	41.0	995.4	70.8	8.1			
				80	1050.5	52.6	871.5	100.2	5.9	2.8	6.4	49.0	1067.5	49.8	898.0	93.6	6.3	6.0	13.8	48.6	1076.1	48.4	911.1	90.3	6.5	10.4	24.1	48.5
				100	996.3	64.3	777.2	119.2	4.5	2.8	6.4	50.2	1012.4	60.7	805.5	113.0	4.9	6.0	13.8	49.8	1020.7	59.0	819.6	109.8	5.1	10.4	24.1	49.6
				120	935.5	79.4	664.7	138.1	3.5	2.8	6.4	51.6	952.0	75.1	695.9	132.3	3.7	6.0	13.8	51.2	960.2	73.0	711.3	129.3	3.9	10.4	24.1	51.0
				130	901.0	88.3	599.8	147.5	3.0	2.8	6.4	52.4	919.0	83.7	633.5	141.9	3.2				927.7	81.5	650.1	139.0	3.3	10.4	24.1	51.8
	210	9.6	22.2	60	1134.8	44.4	983.6	81.7	7.5	2.8	6.4	50.7	1154.3	42.3	1010.2	74.7	8.0				1164.1	41.4	1023.3	71.1	8.3			
				80	1071.2	52.9	890.9	100.6	5.9	2.8	6.4	51.5	1090.1	50.1	919.4	93.9	6.4	6.0	13.8	51.3	1099.7	48.8	933.7	90.5	6.6	10.4	24.1	51.1
				100	1012.4	64.6	792.1	119.5	4.6	2.8	6.4	52.5	1030.1	61.0	822.2	113.2	5.0	6.0	13.8	52.2	1039.2	59.3	837.3	110.0	5.1	10.4	24.1	52.1
				120	946.9	79.7	675.2	138.4	3.5	2.8	6.4	53.6	964.9	75.4	708.0	132.5	3.8	6.0	13.8	53.3	973.9	73.2	724.2	129.4	3.9	10.4	24.1	53.1
				130	910.2	88.6	608.1	147.7	3.0	2.8	6.4	54.2	929.5	83.9	643.4	142.0	3.2				939.0	81.6	660.7	139.1	3.4	10.4	24.1	53.7
70	105	2.5	5.9	60	1195.4	45.4	1040.7	82.8	7.7	2.8	6.4	50.2	1213.7	43.2	1066.7	75.4	8.2	6.0	13.8	49.7	1222.9	42.2	1079.4	71.7	8.5			
				80	1137.8	54.1	953.4	101.9	6.2	2.8	6.4	51.9	1156.0	51.1	982.0	94.8	6.6	6.0	13.8	51.3	1165.3	49.6	996.2	91.2	6.9	10.4	24.1	51.1
				100	1083.3	66.1	858.1	120.9	4.8	2.8	6.4	53.7	1101.1	62.1	889.3	114.2	5.2	6.0	13.8	53.1	1110.1	60.3	904.8	110.7	5.4	10.4	24.1	52.8
				120	1019.6	81.5	741.8	139.8	3.7	2.8	6.4	55.9	1038.8	76.7	777.3	133.4	4.0	6.0	13.8	55.2	1048.3	74.4	794.7	130.2	4.1	10.4	24.1	54.9
				130	981.9	90.6	673.1	149.1	3.2	2.8	6.4	57.2	1003.5	85.4	712.2	143.0	3.4				1013.9	82.9	731.2	139.9	3.6	10.4	24.1	56.1
	158	5.5	12.8	60	1265.3	46.6	1106.4	84.2	8.0	2.8	6.4	56.0	1289.7	44.3	1138.6	76.4	8.5	6.0	13.8	55.6	1302.0	43.3	1154.6	72.4	8.8			
				80	1194.2	55.2	1006.0	103.0	6.3	2.8	6.4	57.2	1217.8	52.1	1040.5	95.6	6.9	6.0	13.8	56.8	1229.9	50.6	1057.7	91.8	7.1	10.4	24.1	56.6
				100	1127.3	67.0	898.8	121.8	4.9	2.8	6.4	58.6	1150.0	63.0	935.4	114.8	5.4	6.0	13.8	58.1	1161.5	61.0	953.6	111.2	5.6	10.4	24.1	57.9
				120	1051.1	82.3	770.5	140.4	3.7	2.8	6.4	60.2	1074.7	77.4	810.8	133.9	4.1	6.0	13.8	59.7	1086.5	75.0	830.7	130.5	4.2	10.4	24.1	59.5
	210	9.6	22.2	60	1299.5	47.3	1138.5	84.9	8.1	2.8	6.4	59.2	1327.2	44.9	1174.2	76.9	8.7	6.0	13.8	58.8	1341.4	43.9	1192.0	72.8	9.0			
				80	1221.4	55.8	1031.4	103.5	6.4	2.8	6.4	60.2	1247.9	52.5	1069.0	96.0	7.0	6.0	13.8	59.8	1261.6	51.0	1087.8	92.1	7.3	10.4	24.1	59.6
				100	1139.4	67.3	909.9	122.1	5.0	2.8	6.4	61.3	1167.6	63.3	951.9	115.1	5.4	6.0	13.8	60.9	1182.3	61.3	973.3	111.4	5.7	10.4	24.1	60.7
				120	1048.2	82.3	767.8	140.4	3.7				1076.0	77.5	811.9	133.9	4.1	6.0	13.8	62.3	1090.0	75.1	834.0	130.6	4.3	10.4	24.1	62.1

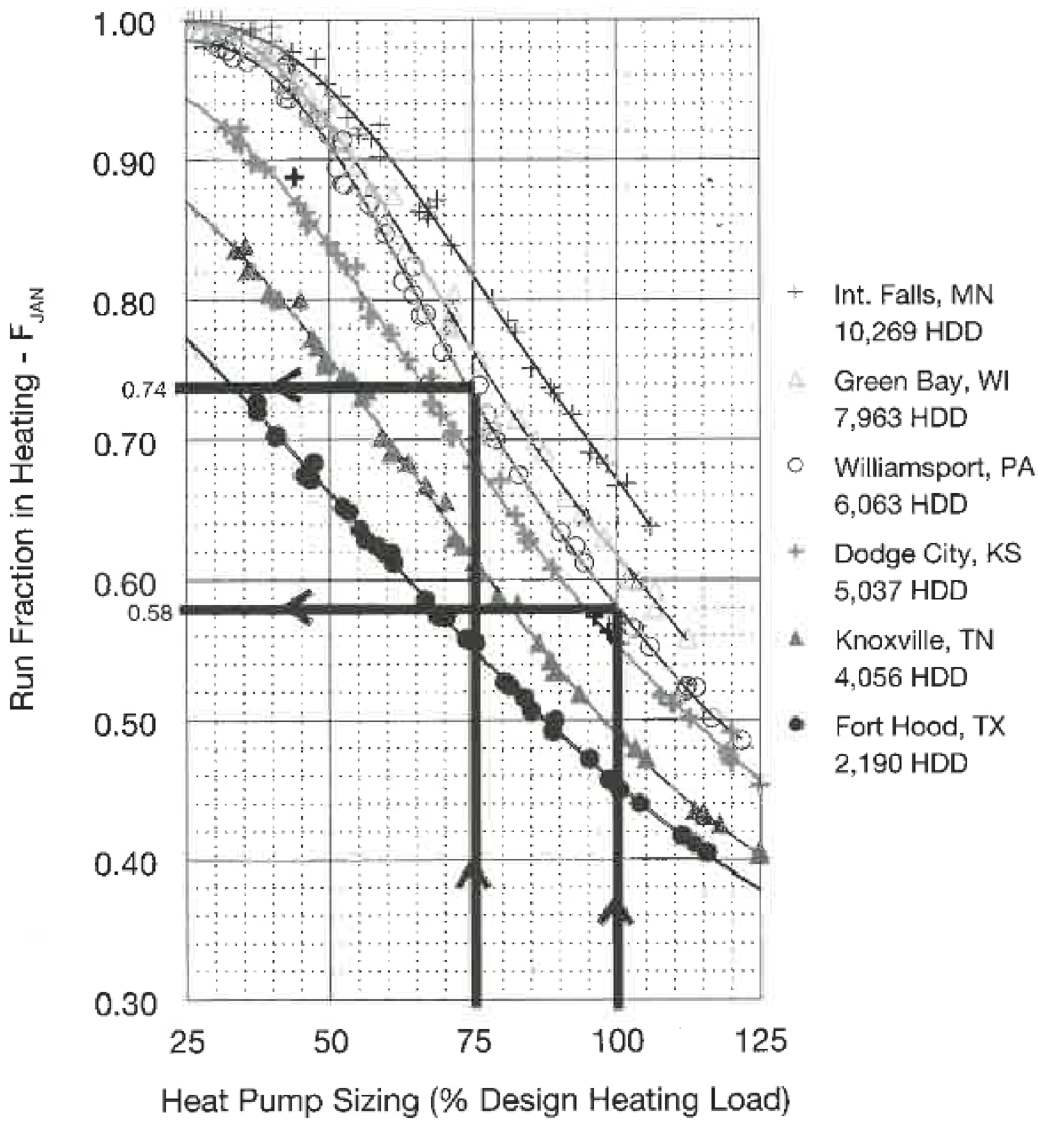
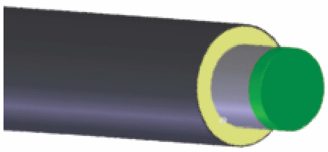


Figure B.1 - Heating Run Fraction vs. Heat Pumps Sizing for Various Heating Degree Day Values (adapted from IGSHPA, 2009).

Appendix B: Supporting Documentation for Chapter 6

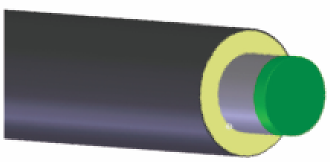
Table B.3 - Elisteel Pipes (length = 16 m) for insulation series 1, 2, and 3, where DN = nominal diameter, d = outside diameter, and S = thickness (Steel Pipes, 2013).

Pipe, 16 metre
isolation serie 1



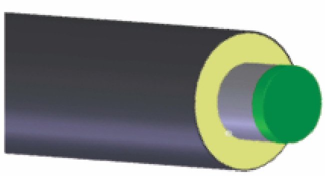
ART.NO.	STEEL PIPE			CASING PIPE		PUR	LENGTH	WEIGHT
		d	S1	D	S2	S3	L	
	DN	[mm]	[mm]	[mm]	[mm]	[mm]	[m]	[kg/pc]
1.103.100	100	114,3	3,6	200	3,2	39,7	16,0	213
1.103.125	125	139,7	3,6	225	3,4	39,3	16,0	259
1.103.150	150	168,3	4,0	250	3,6	37,3	16,0	334
1.103.200	200	219,1	4,5	315	4,1	43,9	16,0	491
1.103.250	250	273,0	5,0	400	4,8	58,7	16,0	703
1.103.300	300	323,9	5,6	450	5,2	57,9	16,0	908
1.103.350	350	355,6	5,6	500	5,6	66,6	16,0	1026
1.103.400	400	406,4	6,3	560	6,0	70,8	16,0	1298
1.103.450	450	457	6,3	560	6,0	45,5	16,0	1375
1.103.500	500	508	6,3	630	6,6	54,4	16,0	1573
1.103.600	600	610	7,1	710	7,2	42,8	16,0	2034

Pipe, 16 metre
isolation serie 2



ART.NO.	STEEL PIPE			CASING PIPE		PUR	LENGTH	WEIGHT
		d	S1	D	S2	S3	L	
	DN	[mm]	[mm]	[mm]	[mm]	[mm]	[m]	[kg/pc]
1.203.100	100	114,3	3,6	225	3,4	52,0	16,0	230
1.203.125	125	139,7	3,6	250	3,6	51,6	16,0	278
1.203.150	150	168,3	4,0	280	3,9	52,0	16,0	360
1.203.200	200	219,1	4,5	355	4,5	63,5	16,0	533
1.203.250	250	273,0	5,0	450	5,2	83,3	16,0	767
1.203.300	300	323,9	5,6	500	5,6	82,5	16,0	979
1.203.350	350	355,6	5,6	560	6,0	96,2	16,0	1119
1.203.400	400	406,4	6,3	630	6,6	105,2	16,0	1423
1.203.450	450	457	6,3	630	6,6	79,9	16,0	1500
1.203.500	500	508	6,3	710	7,2	93,8	16,0	1731
1.203.600	600	610	7,1	800	7,9	87,1	16,0	2234

Pipe, 16 metre
isolation serie 3



ART.NO.	STEEL PIPE			CASING PIPE		PUR	LENGTH	WEIGHT
		d	S1	D	S2	S3	L	
	DN	[mm]	[mm]	[mm]	[mm]	[mm]	[m]	[kg/pc]
1.303.100	100	114,3	3,6	250	3,6	64,3	16,0	249
1.303.125	125	139,7	3,6	280	3,9	66,3	16,0	304
1.303.150	150	168,3	4,0	315	4,1	69,3	16,0	391
1.303.200	200	219,1	4,5	400	4,8	85,7	16,0	584
1.303.250	250	273,0	5,0	500	5,6	107,9	16,0	838
1.303.300	300	323,9	5,6	560	6,0	112,1	16,0	1073
1.303.350	350	355,6	5,6	630	6,6	130,6	16,0	1244
1.303.400	400	406,4	6,3	710	7,2	144,6	16,0	1580
1.303.450	450	457	6,3	710	7,2	119,3	16,0	1658
1.303.500	500	508	6,3	800	7,9	138,1	16,0	1931
1.303.600	600	610	7,1	900	8,7	136,3	16,0	2485

Appendix B: Supporting Documentation for Chapter 6

Table B.4 - Summary of performance data for ClimateMaster TMW036 (60Hz I-P, HFC-410A) for one operating temperature in both cooling and heating mode from submittal data (ClimateMaster, 2015; 2016).

Residential	
C. Mechanical Equipment Selection - Tranquility Modular Water-to-Water (TMW) Size 036	
Heat Pump Brand/Model	ClimateMaster/TMW036
Heat Pump Tonnage - (Tons)	3
Heat Pump Coefficient of Performance (COP_D) in Heating Mode - (-)	3.4
Source Entering Water Temperature ($EWT_{S,H}$) in Heating Mode - (˚F)	30
Source Leaving Water Temperature ($LWT_{S,H}$) in Heating Mode - (˚F)	25.6
Source Flow Rate of Heat Pump - (GPM_S)	9
Load Flow Rate of Heat Pump - (GPM_L)	9
Density (ρ_{fluid}) of Heat Exchanger Fluid - (kg/m^3)	1060
Load Entering Water Temperature ($EWT_{L,H}$) in Heating Mode - (˚F)	100
Load Leaving Water Temperature ($LWT_{L,H}$) in Heating Mode - (˚F)	106.2
Electric Consumption of Heat Pump Unit in Heating Mode - (kW)	2.37
Heating Capacity (HC_{HP}) of the Heat Pump Unit in Heating Mode - (Btu/hr)	27700
Heat of Extraction (HE_{HP}) of the Heat Pump in Heating Mode - (Btu/hr)	19600
Heat Pump Coefficient of Performance (EER_D) in Cooling Mode - (-)	16.3
Source Entering Water Temperature ($EWT_{S,C}$) in Cooling Mode - (˚F)	80
Source Leaving Water Temperature ($LWT_{S,C}$)in Cooling Mode - (˚F)	88.7
Load Entering Water Temperature ($EWT_{L,C}$) in Cooling Mode - (˚F)	50
Load Leaving Water Temperature ($LWT_{L,C}$) in Cooling Mode - (˚F)	42.9
Electric Consumption of Heat Pump Unit in Cooling Mode - (kW)	2.02
Cooling Capacity (CC_{HP}) of the Heat Pump Unit in Cooling Mode - (Btu/hr)	32100
Heat of Rejection (HR_{HP}) of the Heat Pump in Cooling Mode - (Btu/hr)	39000

Table B.5 - Submittal data for ClimateMaster TMW036 (60Hz I-P, HFC-410A) for a range of operating temperatures in cooling mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 4.5 GPM							Flow 6.8 GPM							Flow 9.0 GPM						
	GPM	WPD			TC Mb-tuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
50	4.5	1.3	3.1	50	32.5	1.49	37.6	35.6	21.8	0.6	1.4	34.5	1.52	39.7	39.8	22.7	1.4	3.2	35.3	1.5	40.5	42.1	23.2	2.6	5.9
				60	36.8	1.53	42.0	43.6	24.1	0.5	1.2	38.4	1.54	43.6	48.6	24.9	1.3	3.1	39.2	1.5	44.5	51.3	25.3	2.5	5.8
				70	40.4	1.55	45.7	52.0	26.0	0.5	1.1	41.6	1.56	47.0	57.7	26.6	1.3	2.9	42.4	1.6	47.8	60.6	27.0	2.4	5.6
				80	43.2	1.57	48.6	60.8	27.5	0.4	0.9	44.2	1.58	49.6	66.9	28.0	1.2	2.8	44.8	1.6	50.3	70.0	28.1	2.3	5.4
				90	45.1	1.58	50.5	69.9	28.6	0.3	0.8	46.2	1.60	51.7	76.3	28.9	1.1	2.6	46.6	1.6	52.1	79.7	28.9	2.2	5.1
	6.8	3.4	7.8	50	32.9	1.41	37.7	35.4	23.3	0.6	1.4	34.9	1.44	39.8	39.7	24.2	1.4	3.2	35.8	1.4	40.7	42.0	24.8	2.6	5.9
				60	37.3	1.45	42.2	43.4	25.7	0.5	1.2	38.9	1.46	43.9	48.5	26.6	1.3	3.1	39.7	1.5	44.7	51.2	27.1	2.5	5.8
				70	40.9	1.47	46.0	51.8	27.8	0.5	1.1	42.2	1.48	47.2	57.5	28.4	1.3	2.9	42.9	1.5	48.0	60.5	28.8	2.4	5.6
				80	43.8	1.49	48.9	60.5	29.4	0.4	0.9	44.8	1.50	49.9	66.7	29.9	1.2	2.8	45.4	1.5	50.6	69.9	30.0	2.3	5.4
				90	45.7	1.50	50.8	69.7	30.5	0.3	0.8	Operation not recommended													
	9.0	6.0	13.9	50	33.3	1.33	37.8	35.2	25.1	0.6	1.4	35.4	1.35	40.0	39.5	26.1	1.4	3.2	36.2	1.4	40.9	41.9	26.8	2.6	5.9
				60	37.8	1.36	42.4	43.2	27.8	0.5	1.2	39.4	1.37	44.0	48.3	28.7	1.3	3.1	40.2	1.4	44.9	51.1	29.2	2.5	5.8
				70	41.5	1.38	46.2	51.6	30.0	0.5	1.1	42.7	1.39	47.5	57.3	30.7	1.3	2.9	43.5	1.4	48.3	60.3	31.1	2.4	5.6
				80	44.3	1.40	49.1	60.3	31.7	0.4	0.9	45.4	1.41	50.2	66.6	32.3	1.2	2.8	46.0	1.4	50.8	69.8	32.5	2.3	5.4
				90	46.3	1.41	51.1	69.4	33.0	0.3	0.8														
70	4.5	1.0	2.3	50	30.1	1.96	36.8	36.6	15.3	0.6	1.4	32.1	1.95	38.8	40.5	16.4	1.4	3.2	33.0	2.0	39.7	42.7	16.7	2.6	5.9
				60	34.1	1.98	40.9	44.8	17.2	0.5	1.2	37.6	1.96	44.3	48.9	19.2	1.3	3.1	36.6	2.0	43.3	51.9	18.7	2.5	5.8
				70	39.0	2.01	45.9	52.7	19.4	0.5	1.1	41.7	1.98	48.5	57.6	21.0	1.3	2.9	39.9	2.0	46.7	61.1	19.9	2.4	5.6
				80	42.7	2.03	49.7	61.0	21.1	0.4	1.0	45.4	2.01	52.3	66.5	22.5	1.2	2.8	42.9	2.0	49.8	70.5	21.1	2.3	5.4
				90	46.2	2.05	53.2	69.5	22.5	0.3	0.8														
	6.8	2.8	6.5	50	30.5	1.86	36.8	36.5	16.4	0.6	1.4	32.5	1.85	38.8	40.4	17.5	1.4	3.2	33.4	1.9	39.8	42.6	17.8	2.6	5.9
				60	34.6	1.88	41.0	44.6	18.4	0.5	1.2	38.1	1.86	44.4	48.7	20.4	1.3	3.1	37.1	1.9	43.4	51.8	19.9	2.5	5.8
				70	39.5	1.90	46.0	52.4	20.8	0.5	1.1	42.3	1.88	48.7	57.5	22.4	1.3	2.9	40.4	1.9	46.9	61.0	21.3	2.4	5.6
				80	43.3	1.93	49.9	60.8	22.5	0.4	0.9	46.0	1.91	52.5	66.4	24.1	1.2	2.8	43.4	1.9	50.0	70.3	22.5	2.3	5.4
				90	46.8	1.95	53.4	69.2	24.0	0.3	0.8														
	9.0	5.1	11.9	50	30.8	1.74	36.8	36.3	17.7	0.6	1.4	32.9	1.74	38.8	40.2	19.0	1.4	3.2	33.8	1.8	39.8	42.5	19.3	2.6	5.9
				60	35.0	1.76	41.0	44.4	19.9	0.5	1.2	38.6	1.75	44.5	48.6	22.1	1.3	3.1	37.5	1.7	43.5	51.7	21.5	2.5	5.8
				70	40.0	1.78	46.1	52.2	22.4	0.5	1.1	42.8	1.77	48.8	57.3	24.2	1.3	2.9	40.9	1.8	47.0	60.9	23.0	2.4	5.6
				80	43.8	1.81	50.0	60.5	24.3	0.4	0.9	46.6	1.79	52.7	66.2	26.0	1.2	2.8	44.0	1.8	50.2	70.2	24.3	2.3	5.4
				90	47.4	1.83	53.6	68.9	26.0	0.3	0.8														
80	4.5	0.9	2.1	50	28.5	2.26	36.2	37.3	13.0	0.6	1.4	30.5	2.27	38.3	36.4	13.8	1.4	3.2	31.3	2.27	39.1	36.1	14.1	2.6	5.9
				60	32.6	2.28	40.4	45.5	14.7	0.5	1.2	35.8	2.28	43.6	44.1	16.1	1.3	3.1	35.1	2.26	42.8	44.4	15.9	2.5	5.8
				70	37.6	2.30	45.5	53.3	16.7	0.5	1.1	40.3	2.30	48.2	52.1	17.9	1.3	2.9	38.6	2.30	46.5	52.8	17.2	2.4	5.6
				80	41.6	2.32	49.5	61.5	18.3	0.4	1.0	44.2	2.33	52.1	60.4	19.4	1.2	2.8	42.0	2.33	49.9	61.3	18.3	2.3	5.4
				90	45.2	2.35	53.2	69.9	19.6	0.3	0.8														
	6.75	2.6	6.0	50	28.9	2.14	36.2	41.4	13.8	0.6	1.4	30.9	2.16	38.2	40.8	14.7	1.4	3.2	31.7	2.16	39.1	40.6	15.1	2.6	5.9
				60	33.0	2.16	40.4	50.2	15.6	0.5	1.2	36.2	2.16	43.6	49.3	17.2	1.3	3.1	35.5	2.14	42.8	49.5	17.0	2.5	5.8
				70	38.1	2.18	45.6	58.7	17.8	0.5	1.1	40.8	2.18	48.3	57.9	19.2	1.3	2.9	39.1	2.18	46.6	58.4	18.3	2.4	5.6
				80	42.1	2.21	49.7	67.5	19.5	0.4	0.9	44.7	2.21	52.3	66.7	20.7	1.2	2.8	42.5	2.21	50.1	67.4	19.6	2.3	5.4
				90	45.8	2.23	53.3	76.4	20.9	0.3	0.8														
	9.0	4.8	11.1	50	29.3	2.01	36.1	43.5	14.9	0.6	1.4	31.3	2.02	38.2	43.0	15.9	1.4	3.2	32.1	2.02	39.0	42.9	16.3	2.6	5.9
				60	33.5	2.03	40.4	52.6	16.9	0.5	1.2	36.7	2.03	43.6	51.8	18.6	1.3	3.1	36.0	2.01	42.8	52.0	18.3	2.5	5.8
				70	38.6	2.05	45.6	61.4	19.3	0.5	1.1	41.3	2.05	48.3	60.8	20.7	1.3	2.9	39.6	2.04	46.6	61.2	19.8	2.4	5.6
				80	42.7	2.07	49.7	70.5	21.0	0.4	0.9	45.3	2.07	52.4	69.9	22.3	1.2	2.8	43.1	2.08	50.1	70.4	21.1	2.3	5.4
				90	46.3	2.09	53.4	79.7	22.6	0.3	0.8														

Table B.5 Continued - Submittal data for ClimateMaster TMW036 (60Hz I-P, HFC-410A) for a range of operating temperatures in heating mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 4.5 GPM							Flow 6.8 GPM							Flow 9.0 GPM						
	GPM	WPD			HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
20	9.0	7.7	17.9	60	26.1	1.53	20.9	71.6	5.0	0.5	1.2	26.4	1.45	21.5	67.8	5.3	1.3	3.1	26.5	1.41	21.7	65.9	5.5	2.5	5.8
				80	25.7	1.96	19.0	91.4	3.8	0.4	0.9	25.9	1.86	19.6	87.7	4.1	1.2	2.8	25.9	1.81	19.8	85.8	4.2	2.3	5.4
				100	25.0	2.56	16.3	111.1	2.9	0.3	0.7	25.0	2.42	16.7	107.4	3.0	1.1	2.5	24.9	2.36	16.9	105.5	3.1	2.1	4.9
30	4.5	1.7	4.0	60	27.1	1.54	21.9	72.1	5.2	0.5	1.2	27.5	1.45	22.5	68.1	5.5	1.3	3.1	27.6	1.42	22.7	66.1	5.7	2.5	5.8
				80	26.7	1.97	20.0	91.9	4.0	0.4	0.9	27.0	1.86	20.6	88.0	4.2	1.2	2.8	27.0	1.81	20.8	86.0	4.4	2.3	5.4
				100	26.1	2.56	17.3	111.6	3.0	0.3	0.7	26.1	2.43	17.8	107.7	3.2	1.1	2.5	26.0	2.36	18.0	105.8	3.2	2.1	4.9
				120	25.1	3.32	13.8	131.2	2.2	0.2	0.5	24.9	3.14	14.2	127.4	2.3	0.9	2.1	24.7	3.06	14.3	125.5	2.4	1.8	4.3
	6.8	4.1	9.4	60	28.4	1.54	23.2	72.6	5.4	0.5	1.2	28.8	1.46	23.8	68.5	5.8	1.3	3.1	28.9	1.42	24.1	66.4	6.0	2.5	5.8
				80	27.9	1.97	21.2	92.4	4.2	0.4	0.9	28.2	1.87	21.8	88.4	4.4	1.2	2.8	28.2	1.82	22.0	86.3	4.6	2.3	5.4
				100	27.1	2.57	18.3	112.0	3.1	0.3	0.7	27.2	2.43	18.9	108.0	3.3	1.1	2.5	27.1	2.37	19.0	106.0	3.4	2.1	4.9
				120	25.9	3.33	14.6	131.5	2.3	0.2	0.5	25.7	3.15	15.0	127.6	2.4	0.9	2.1	25.6	3.07	15.1	125.7	2.4	1.8	4.3
	9.0	7.1	16.4	60	29.2	1.54	23.9	73.0	5.5	0.5	1.2	29.6	1.46	24.6	68.8	5.9	1.3	3.1	29.7	1.42	24.8	66.6	6.1	2.5	5.8
				80	28.6	1.98	21.9	92.7	4.2	0.4	0.9	28.9	1.87	22.5	88.6	4.5	1.2	2.8	28.9	1.82	22.7	86.4	4.7	2.3	5.4
				100	27.7	2.58	18.9	112.3	3.2	0.3	0.7	27.8	2.44	19.5	108.2	3.3	1.1	2.5	27.7	2.37	19.6	106.2	3.4	2.1	4.9
				120	26.4	3.34	15.0	131.7	2.3	0.2	0.5	26.2	3.16	15.4	127.8	2.4	0.9	2.1	26.1	3.08	15.6	125.8	2.5	1.8	4.3
40	4.5	1.5	3.5	60	30.7	1.41	25.9	71.5	6.4	0.5	1.2	31.2	1.33	26.7	67.9	6.9	1.3	3.1	31.3	1.30	26.9	66.0	7.1	2.5	5.8
				80	30.6	1.81	24.4	90.8	4.9	0.4	0.9	31.0	1.72	25.1	87.4	5.3	1.2	2.8	31.1	1.67	25.3	85.6	5.4	2.3	5.4
				100	29.9	2.39	21.7	109.7	3.7	0.3	0.7	30.1	2.27	22.4	106.6	3.9	1.1	2.5	30.1	2.21	22.6	105.0	4.0	2.1	4.9
				120	28.8	3.17	18.0	128.0	2.7	0.2	0.5	28.7	3.00	18.5	125.5	2.8	0.9	2.1	28.6	2.92	18.6	124.1	2.9	1.8	4.3
	6.8	3.7	8.6	60	32.6	1.48	27.5	72.2	6.4	0.5	1.2	33.1	1.40	28.3	68.4	6.9	1.3	3.1	33.3	1.37	28.6	66.4	7.1	2.5	5.8
				80	32.1	1.90	25.6	91.4	4.9	0.4	0.9	32.5	1.80	26.3	87.8	5.3	1.2	2.8	32.6	1.75	26.6	85.9	5.4	2.3	5.4
				100	31.1	2.49	22.6	110.0	3.7	0.3	0.7	31.3	2.36	23.3	106.9	3.9	1.1	2.5	31.3	2.30	23.5	105.2	4.0	2.1	4.9
				120	29.7	3.26	18.6	128.3	2.7	0.2	0.5	29.7	3.09	19.1	125.7	2.8	0.9	2.1	29.6	3.01	19.3	124.3	2.9	1.8	4.3
	9.0	6.5	15.1	60	34.5	1.55	29.2	73.0	6.5	0.5	1.2	35.0	1.47	30.0	68.9	7.0	1.3	3.1	35.2	1.43	30.3	66.7	7.2	2.5	5.8
				80	33.6	1.99	26.8	91.9	4.9	0.4	0.9	34.0	1.89	27.6	88.2	5.3	1.2	2.8	34.1	1.84	27.8	86.2	5.4	2.3	5.4
				100	32.3	2.59	23.5	110.4	3.7	0.3	0.7	32.5	2.45	24.2	107.2	3.9	1.1	2.5	32.5	2.39	24.4	105.4	4.0	2.1	4.9
				120	30.7	3.36	19.2	128.5	2.7	0.2	0.5	30.6	3.18	19.8	125.9	2.8	0.9	2.1	30.5	3.09	20.0	124.4	2.9	1.8	4.3
50	4.5	1.3	3.1	60	35.9	1.55	30.6	76.0	6.8	0.5	1.2	36.5	1.47	31.5	70.8	7.3	1.3	3.1	36.7	1.43	31.8	68.2	7.5	2.5	5.8
				80	35.0	2.00	28.2	95.6	5.1	0.4	0.9	35.5	1.89	29.0	90.5	5.5	1.2	2.8	35.6	1.84	29.3	87.9	5.7	2.3	5.4
				100	33.8	2.60	24.9	115.0	3.8	0.3	0.7	34.0	2.46	25.6	110.1	4.1	1.1	2.5	34.0	2.39	25.9	107.6	4.2	2.1	4.9
				120	32.2	3.36	20.7	134.3	2.8	0.2	0.5	32.1	3.18	21.3	129.5	3.0	0.9	2.1	32.1	3.09	21.5	127.1	3.0	1.8	4.3
				130	Operation not recommended							31.1	3.59	18.8	139.2	2.5	0.8	1.9	30.9	3.50	19.0	136.9	2.6	1.7	3.9
	6.75	3.4	7.8	60	37.7	1.56	32.4	76.8	7.1	0.5	1.2	38.4	1.48	33.3	71.4	7.6	1.3	3.1	38.5	1.44	33.6	68.6	7.9	2.5	5.8
				80	36.6	2.00	29.8	96.3	5.4	0.4	0.9	37.1	1.89	30.7	91.0	5.7	1.2	2.8	37.3	1.84	31.0	88.3	5.9	2.3	5.4
				100	35.2	2.60	26.3	115.6	4.0	0.3	0.7	35.5	2.46	27.1	110.5	4.2	1.1	2.5	35.5	2.40	27.3	107.9	4.3	2.1	4.9
				120	33.4	3.37	21.9	134.8	2.9	0.2	0.5	33.4	3.19	22.5	129.9	3.1	0.9	2.1	33.3	3.10	22.7	127.4	3.1	1.8	4.3
				130								32.2	3.60	19.9	139.5	2.6	0.8	1.9	32.0	3.51	20.1	137.1	2.7	1.7	3.9
	9.0	6.0	13.9	60	38.6	1.56	33.3	77.2	7.2	0.5	1.2	39.3	1.48	34.3	71.7	7.8	1.3	3.1	39.5	1.44	34.6	68.8	8.0	2.5	5.8
				80	37.5	2.01	30.7	96.7	5.5	0.4	0.9	38.0	1.90	31.6	91.3	5.9	1.2	2.8	38.2	1.85	31.9	88.5	6.1	2.3	5.4
				100	36.0	2.61	27.1	116.0	4.0	0.3	0.7	36.3	2.47	27.9	110.8	4.3	1.1	2.5	36.3	2.40	28.1	108.1	4.4	2.1	4.9
				120	34.0	3.37	22.5	135.1	3.0	0.2	0.5	34.1	3.19	23.2	130.1	3.1	0.9	2.1	34.0	3.11	23.4	127.6	3.2	1.8	4.3
				130								32.8	3.61	20.5	139.7	2.7	0.8	1.9	32.6	3.52	20.6	137.3	2.7	1.7	3.9

Table B.5 Continued - Submittal data for ClimateMaster TMW036 (60Hz I-P, HFC-410A) for a range of operating temperatures in heating mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 4.5 GPM							Flow 6.8 GPM							Flow 9.0 GPM						
	GPM	WPD			HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
60	4.5	1.2	2.7	60	39.0	1.57	33.6	77.3	7.3	0.5	1.2	39.7	1.48	34.6	71.8	7.8	1.3	3.1	39.9	1.44	34.9	68.9	8.1	2.5	5.8
				80	38.6	2.01	31.8	97.2	5.6	0.4	0.9	39.2	1.90	32.7	91.6	6.0	1.2	2.8	39.3	1.85	33.0	88.7	6.2	2.3	5.4
				100	37.6	2.61	28.7	116.7	4.2	0.3	0.7	38.0	2.47	29.6	111.3	4.5	1.1	2.5	38.0	2.40	29.8	108.5	4.6	2.1	4.9
				120	36.0	3.37	24.5	136.0	3.1	0.2	0.5	36.1	3.19	25.2	130.7	3.3	0.9	2.1	36.0	3.11	25.4	128.0	3.4	1.8	4.3
				130	Operation not recommended							34.8	3.61	22.5	140.3	2.8	0.8	1.9	34.7	3.51	22.7	137.7	2.9	1.7	3.9
	6.75	3.1	7.1	60	40.6	1.57	35.3	78.1	7.6	0.5	1.2	41.4	1.49	36.3	72.3	8.2	1.3	3.1	41.6	1.45	36.6	69.2	8.4	2.5	5.8
				80	40.2	2.01	33.4	97.9	5.9	0.4	0.9	40.8	1.90	34.3	92.1	6.3	1.2	2.8	41.0	1.85	34.6	89.1	6.5	2.3	5.4
				100	39.1	2.61	30.2	117.4	4.4	0.3	0.7	39.5	2.47	31.0	111.7	4.7	1.1	2.5	39.5	2.41	31.3	108.8	4.8	2.1	4.9
				120	37.2	3.38	25.7	136.5	3.2	0.2	0.5	37.3	3.20	26.4	131.1	3.4	0.9	2.1	37.3	3.11	26.6	128.3	3.5	1.8	4.3
				130								35.9	3.62	23.6	140.6	2.9	0.8	1.9	35.8	3.52	23.8	138.0	3.0	1.7	3.9
	9.0	5.6	12.8	60	41.5	1.57	36.1	78.4	7.7	0.5	1.2	42.2	1.49	37.2	72.5	8.3	1.3	3.1	42.4	1.45	37.5	69.4	8.6	2.5	5.8
				80	41.0	2.01	34.1	98.2	6.0	0.4	0.9	41.6	1.91	35.1	92.3	6.4	1.2	2.8	41.8	1.86	35.5	89.3	6.6	2.3	5.4
				100	39.8	2.62	30.9	117.7	4.5	0.3	0.7	40.2	2.48	31.8	111.9	4.8	1.1	2.5	40.3	2.41	32.0	109.0	4.9	2.1	4.9
				120	37.8	3.38	26.3	136.8	3.3	0.2	0.5	38.0	3.20	27.0	131.2	3.5	0.9	2.1	37.9	3.12	27.3	128.4	3.6	1.8	4.3
				130								36.5	3.62	24.1	140.8	3.0	0.8	1.9	36.4	3.53	24.4	138.1	3.0	1.7	3.9
70	4.5	1.0	2.3	60	42.1	1.58	36.7	78.7	7.8	0.5	1.2	42.9	1.49	37.8	72.7	8.4	1.3	3.1	43.1	1.46	38.1	69.6	8.7	2.5	5.8
				80	42.4	2.02	35.5	98.8	6.2	0.4	0.9	43.0	1.91	36.5	92.7	6.6	1.2	2.8	43.2	1.86	36.8	89.6	6.8	2.3	5.4
				100	41.6	2.62	32.7	118.5	4.7	0.3	0.7	42.1	2.48	33.6	112.5	5.0	1.1	2.5	42.2	2.41	33.9	109.4	5.1	2.1	4.9
				120	39.8	3.38	28.3	137.7	3.5	0.2	0.5	40.0	3.20	29.1	131.9	3.7	0.9	2.1	40.0	3.12	29.4	128.9	3.8	1.8	4.3
				130								38.6	3.62	26.3	141.4	3.1	0.8	1.9	38.5	3.53	26.5	138.6	3.2	1.7	3.9
	6.75	2.8	6.5	60	43.6	1.58	38.2	79.4	8.1	0.5	1.2	44.4	1.50	39.3	73.2	8.7	1.3	3.1	44.7	1.46	39.7	69.9	9.0	2.5	5.8
				80	43.8	2.02	36.9	99.5	6.4	0.4	0.9	44.5	1.91	38.0	93.2	6.8	1.2	2.8	44.7	1.86	38.4	89.9	7.0	2.3	5.4
				100	43.0	2.62	34.0	119.1	4.8	0.3	0.7	43.5	2.49	35.0	112.9	5.1	1.1	2.5	43.6	2.42	35.3	109.7	5.3	2.1	4.9
				120	41.0	3.39	29.5	138.2	3.5	0.2	0.5	41.3	3.21	30.3	132.2	3.8	0.9	2.1	41.3	3.13	30.6	129.2	3.9	1.8	4.3
				130								39.7	3.63	27.3	141.8	3.2	0.8	1.9	39.7	3.54	27.6	138.8	3.3	1.7	3.9
	9.0	5.1	11.9	60	44.3	1.59	38.9	79.7	8.2	0.5	1.2	45.1	1.50	40.0	73.4	8.8	1.3	3.1	45.4	1.46	40.4	70.1	9.1	2.5	5.8
				80	44.5	2.02	37.6	99.8	6.4	0.4	0.9	45.2	1.92	38.7	93.4	6.9	1.2	2.8	45.4	1.87	39.1	90.1	7.1	2.3	5.4
				100	43.6	2.63	34.6	119.4	4.9	0.3	0.7	44.1	2.49	35.6	113.1	5.2	1.1	2.5	44.2	2.42	36.0	109.8	5.4	2.1	4.9
				120	41.6	3.40	30.0	138.5	3.6	0.2	0.5	41.8	3.22	30.9	132.4	3.8	0.9	2.1	41.8	3.13	31.1	129.3	3.9	1.8	4.3
				130								40.2	3.64	27.8	141.9	3.2	0.8	1.9	40.2	3.54	28.1	138.9	3.3	1.7	3.9
80	4.5	0.9	2.0	60	45.3	1.59	39.8	80.1	8.3	0.5	1.2	46.1	1.51	41.0	73.7	9.0	1.3	3.1	46.4	1.47	41.4	70.3	9.3	2.5	5.8
				80	46.2	2.03	39.2	100.5	6.7	0.4	0.9	46.9	1.92	40.4	93.9	7.2	1.2	2.8	47.1	1.87	40.8	90.5	7.4	2.3	5.4
				100	45.7	2.63	36.7	120.3	5.1	0.3	0.7	46.3	2.49	37.8	113.7	5.4	1.1	2.5	46.4	2.42	38.1	110.3	5.6	2.1	4.9
				120	43.8	3.40	32.2	139.5	3.8	0.2	0.5	44.1	3.22	33.2	133.1	4.0	0.9	2.1	44.2	3.13	33.5	129.8	4.1	1.8	4.3
				130								27.9	3.61	15.6	138.3	2.3	0.8	1.9	27.7	3.51	15.7	136.2	2.3	1.7	3.9
	6.75	2.6	5.9	60	46.6	1.59	41.2	80.7	8.6	0.5	1.2	47.5	1.51	42.4	74.1	9.2	1.3	3.1	47.8	1.47	42.8	70.6	9.5	2.5	5.8
				80	47.5	2.03	40.6	101.1	6.9	0.4	0.9	48.3	1.92	41.7	94.3	7.4	1.2	2.8	48.5	1.87	42.1	90.8	7.6	2.3	5.4
				100	46.9	2.64	37.9	120.9	5.2	0.3	0.7	47.5	2.50	39.0	114.1	5.6	1.1	2.5	47.7	2.43	39.4	110.6	5.8	2.1	4.9
				120	44.9	3.40	33.3	140.0	3.9	0.2	0.5	45.3	3.22	34.3	133.4	4.1	0.9	2.1	45.3	3.14	34.6	130.1	4.2	1.8	4.3
				130								28.5	3.62	16.1	138.4	2.3	0.8	1.9	28.3	3.52	16.3	136.3	2.4	1.7	3.9
	9.0	4.8	11.0	60	47.1	1.60	41.7	81.0	8.7	0.5	1.2	48.1	1.51	42.9	74.2	9.3	1.3	3.1	48.3	1.47	43.3	70.7	9.6	2.5	5.8
				80	48.0	2.03	41.1	101.3	6.9	0.4	0.9	48.8	1.93	42.3	94.5	7.4	1.2	2.8	49.0	1.88	42.7	90.9	7.7	2.3	5.4
				100	47.4	2.64	38.4	121.1	5.3	0.3	0.7	48.1	2.50	39.5	114.2	5.6	1.1	2.5	48.2	2.43	39.9	110.7	5.8	2.1	4.9
				120	45.4	3.41	33.7	140.2	3.9	0.2	0.5	45.7	3.23	34.7	133.5	4.2	0.9	2.1	45.8	3.14	35.0	130.2	4.3	1.8	4.3

Table B.6 - Summary of performance data for ClimateMaster TMW060 (60Hz I-P, HFC-410A) for one operating temperature in both cooling and heating mode from submittal data (ClimateMaster, 2015; 2016).

Commercial (Small)	
C. Mechanical Equipment Selection - Tranquility Modular Water-to-Water (TMW) Size 060	
Heat Pump Brand/Model	ClimateMaster/TMW060
Heat Pump Tonnage - (Tons)	5
Heat Pump Coefficient of Performance (COP_D) in Heating Mode - (-)	3.5
Source Entering Water Temperature ($EWT_{S,H}$) in Heating Mode - (˚F)	30
Source Leaving Water Temperature ($LWT_{S,H}$) in Heating Mode - (˚F)	25.3
Source Flow Rate of Heat Pump - (GPM_S)	15
Load Flow Rate of Heat Pump - (GPM_L)	15
Density (ρ_{fluid}) of Heat Exchanger Fluid - (kg/m³)	1060
Load Entering Water Temperature ($EWT_{L,H}$) in Heating Mode - (˚F)	100
Load Leaving Water Temperature ($LWT_{L,H}$) in Heating Mode - (˚F)	106.4
Electric Consumption of Heat Pump Unit in Heating Mode - (kW)	4.2
Heating Capacity (HC_{HP}) of the Heat Pump Unit in Heating Mode - (Btu/hr)	49700
Heat of Extraction (HE_{HP}) of the Heat Pump in Heating Mode - (Btu/hr)	35400
Heat Pump Coefficient of Performance (EER_D) in Cooling Mode - (-)	13.3
Source Entering Water Temperature ($EWT_{S,C}$) in Cooling Mode - (˚F)	90
Source Leaving Water Temperature ($LWT_{S,C}$)in Cooling Mode - (˚F)	98.3
Load Entering Water Temperature ($EWT_{L,C}$) in Cooling Mode - (˚F)	50
Load Leaving Water Temperature ($LWT_{L,C}$) in Cooling Mode - (˚F)	43.3
Electric Consumption of Heat Pump Unit in Cooling Mode - (kW)	4
Cooling Capacity (CC_{HP}) of the Heat Pump Unit in Cooling Mode - (Btu/hr)	49500
Heat of Rejection (HR_{HP}) of the Heat Pump in Cooling Mode - (Btu/hr)	62200

Table B.7 - Submittal data for ClimateMaster TMW060 (60Hz I-P, HFC-410A) for a range of operating temperatures in cooling mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 7.5 GPM							Flow 11.25 GPM							Flow 15.0 GPM						
	GPM	WPD			TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
50	7.5	1.3	2.9	50	52.6	2.20	60.1	38.2	23.9	1.4	3.3	53.5	2.23	61.1	41.0	24.0	3.5	8.0	55.3	2.25	63.0	42.5	24.6	4.8	11.0
				60	53.2	2.22	60.8	47.1	23.9	1.4	3.2	54.1	2.25	61.7	50.5	24.1	3.3	7.7	55.9	2.27	63.7	52.4	24.7	4.6	10.6
				70	53.8	2.24	61.4	56.0	24.0	1.3	3.0	54.7	2.26	62.4	60.0	24.1	3.2	7.4	56.6	2.29	64.4	62.2	24.7	4.4	10.1
				80	55.5	2.24	63.2	64.7	24.7	1.2	2.9	56.4	2.27	64.1	69.4	24.9	3.1	7.1	58.4	2.29	66.2	72.0	25.5	4.3	9.8
				90	57.2	2.25	64.9	73.5	25.5	1.2	2.7	58.1	2.27	65.9	78.9	25.6	3.0	6.9	60.2	2.29	68.0	81.8	26.3	4.1	9.5
	11.25	3.4	7.9	50	53.4	2.23	61.0	38.0	24.0	1.4	3.3	54.1	2.25	61.8	40.8	24.1	3.5	8.0	56.0	2.27	63.8	42.3	24.7	4.8	11.0
				60	55.5	2.25	63.1	46.7	24.7	1.4	3.2	56.2	2.27	64.0	50.1	24.8	3.3	7.7	58.2	2.29	66.0	52.0	25.4	4.6	10.6
				70	57.5	2.26	65.3	55.4	25.4	1.3	3.0	58.3	2.29	66.1	59.4	25.5	3.2	7.4	60.4	2.31	68.3	61.6	26.1	4.4	10.2
				80	58.1	2.27	65.8	64.3	25.6	1.2	2.9	58.9	2.29	66.7	69.0	25.7	3.1	7.1	60.9	2.31	68.8	71.5	26.4	4.3	9.8
				90	58.6	2.27	66.3	73.2	25.8	1.2	2.7	59.4	2.29	67.2	78.5	25.9	3.0	6.9	61.5	2.31	69.4	81.4	26.6	4.1	9.5
	15.0	6.2	14.2	50	55.6	2.25	63.2	35.8	24.7	1.4	3.3	56.5	2.27	64.2	40.3	24.9	3.5	8.0	57.9	2.29	65.8	42.1	25.2	4.8	11.1
				60	57.5	2.27	65.2	45.0	25.3	1.4	3.2	58.7	2.29	66.6	49.8	25.6	3.3	7.7	61.5	2.31	69.4	51.5	26.6	4.6	10.6
				70	59.4	2.29	67.2	54.1	26.0	1.3	3.0	61.0	2.31	68.9	59.3	26.4	3.2	7.4	65.1	2.33	73.1	60.9	27.9	4.4	10.1
				80	60.3	2.29	68.1	63.5	26.4	1.2	2.9	61.8	2.31	69.7	68.7	26.7	3.1	7.1	65.8	2.34	73.8	70.8	28.2	4.2	9.8
				90	61.3	2.29	69.1	72.8	26.7	1.2	2.7	62.6	2.31	70.5	78.1	27.0	3.0	6.9	66.6	2.34	74.6	80.7	28.5	4.1	9.4
70	7.5	1.1	2.5	50	49.1	2.82	58.7	38.1	17.4	1.4	3.3	50.3	2.85	60.0	41.1	17.7	3.5	8.0	52.0	2.88	61.8	42.9	18.1	4.7	11.0
				60	53.2	2.84	62.9	46.4	18.7	1.4	3.2	54.5	2.87	64.3	50.0	19.0	3.3	7.7	56.3	2.90	66.2	52.3	19.4	4.6	10.5
				70	57.2	2.86	67.0	54.8	20.0	1.3	3.0	58.7	2.89	68.5	59.1	20.3	3.2	7.4	60.6	2.92	70.6	61.7	20.8	4.4	10.1
				80	59.3	2.92	69.3	63.4	20.3	1.2	2.9	60.8	2.95	70.9	68.3	20.6	3.1	7.1	62.9	2.98	73.0	71.4	21.1	4.3	9.8
				90	61.4	2.98	71.6	71.9	20.6	1.2	2.7	63.0	3.01	73.3	77.6	20.9	3.0	6.9	65.1	3.04	75.5	81.1	21.4	4.1	9.5
	11.25	3.0	6.9	50	50.2	2.85	59.9	38.0	17.6	1.4	3.3	51.4	2.88	61.2	41.0	17.8	3.5	8.0	53.1	2.91	63.0	42.8	18.3	4.8	11.0
				60	54.5	2.87	64.3	46.2	19.0	1.4	3.2	55.9	2.90	65.8	49.8	19.3	3.3	7.7	57.7	2.93	67.7	52.1	19.7	4.6	10.6
				70	58.9	2.89	68.8	54.5	20.4	1.3	3.0	60.4	2.92	70.3	58.8	20.7	3.2	7.4	62.4	2.94	72.4	61.4	21.2	4.4	10.2
				80	60.8	2.95	70.8	63.1	20.6	1.2	2.9	62.3	2.98	72.4	68.1	20.9	3.1	7.1	64.4	3.01	74.6	71.1	21.4	4.3	9.9
				90	62.6	3.01	72.9	71.7	20.8	1.2	2.7	64.2	3.04	74.5	77.3	21.1	3.0	6.9	66.3	3.07	76.8	80.8	21.6	4.1	9.6
	15.0	5.5	12.8	50	51.2	2.88	61.0	36.9	17.8	1.4	3.3	53.3	2.91	63.2	40.8	18.3	3.5	8.0	54.3	2.94	64.3	42.6	18.5	4.8	11.0
				60	55.6	2.90	65.5	45.4	19.2	1.4	3.2	57.6	2.93	67.6	49.6	19.7	3.3	7.7	59.4	2.96	69.5	51.8	20.1	4.6	10.6
				70	60.1	2.92	70.1	53.9	20.6	1.3	3.0	61.9	2.94	72.0	58.5	21.0	3.2	7.4	64.5	2.97	74.6	61.1	21.7	4.4	10.1
				80	62.3	2.98	72.5	62.7	20.9	1.2	2.9	64.1	3.01	74.4	67.8	21.3	3.1	7.1	67.1	3.04	77.5	70.6	22.1	4.2	9.8
				90	64.6	3.04	74.9	71.5	21.3	1.2	2.7	66.3	3.07	76.8	77.1	21.6	3.0	6.9	69.8	3.10	80.3	80.2	22.5	4.1	9.5
80	7.5	1.0	2.3	50	47.3	3.13	58.0	38.0	15.1	1.4	3.3	48.7	3.16	59.5	41.1	15.4	3.5	8.0	50.3	3.19	61.2	43.1	15.8	4.7	10.9
				60	53.1	3.15	63.9	46.1	16.9	1.4	3.2	54.7	3.18	65.6	49.8	17.2	3.3	7.7	56.5	3.21	67.5	52.3	17.6	4.6	10.5
				70	58.9	3.17	69.7	54.2	18.6	1.3	3.0	60.7	3.20	71.6	58.6	19.0	3.2	7.4	62.7	3.23	73.7	61.5	19.4	4.4	10.1
				80	61.3	3.25	72.4	62.7	18.8	1.2	2.9	63.1	3.29	74.3	67.8	19.2	3.1	7.1	65.1	3.32	76.5	71.1	19.6	4.3	9.8
				90	63.6	3.34	75.0	71.1	19.0	1.2	2.7	65.4	3.38	77.0	76.9	19.4	3.0	6.9	67.6	3.41	79.2	80.7	19.8	4.1	9.6
	11.25	2.8	6.5	50	48.5	3.16	59.3	38.0	15.3	1.4	3.3	50.0	3.19	60.9	41.1	15.6	3.5	8.0	51.6	3.23	62.6	43.0	16.0	4.8	11.1
				60	54.1	3.18	64.9	46.0	17.0	1.4	3.2	55.7	3.21	66.6	49.7	17.3	3.3	7.7	57.5	3.24	68.6	52.2	17.7	4.6	10.6
				70	59.6	3.20	70.5	54.0	18.7	1.3	3.0	61.4	3.23	72.4	58.4	19.0	3.2	7.4	63.4	3.26	74.5	61.3	19.4	4.4	10.2
				80	62.1	3.29	73.4	62.5	18.9	1.2	2.9	64.0	3.32	75.3	67.6	19.3	3.1	7.1	66.1	3.35	77.5	70.9	19.7	4.3	9.9
				90	64.6	3.38	76.2	71.0	19.1	1.2	2.7	66.6	3.41	78.2	76.8	19.5	3.0	6.9	68.7	3.45	80.5	80.6	19.9	4.2	9.6
	15.0	5.3	12.1	50	49.0	3.19	59.9	37.4	15.3	1.4	3.3	51.7	3.23	62.7	41.0	16.0	3.5	8.0	52.4	3.26	63.5	42.9	16.1	4.8	11.0
				60	54.7	3.21	65.7	45.6	17.0	1.4	3.2	57.1	3.24	68.1	49.5	17.6	3.3	7.7	58.3	3.28	69.5	52.0	17.8	4.6	10.6
				70	60.5	3.23	71.5	53.8	18.7	1.3	3.0	62.4	3.26	73.5	58.1	19.1	3.2	7.4	64.2	3.30	75.4	61.1	19.5	4.4	10.1
				80	63.3	3.32	74.7	62.3	19.1	1.2	2.9	65.3	3.35	76.7	67.4	19.5	3.1	7.1	67.8	3.39	79.3	70.5	20.0	4.3	9.8
				90	66.2	3.41	77.9	70.8	19.4	1.2	2.7	68.2	3.45	79.9	76.7	19.8	3.0	6.9	71.4	3.48	83.2	80.0	20.5	4.1	9.6

Table B.7 Continued - Submittal data for ClimateMaster TMW060 (60Hz I-P, HFC-410A) for a range of operating temperatures in cooling mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 7.5 GPM							Flow 11.25 GPM							Flow 15.0 GPM						
	GPM	WPD			TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
				50	44.8	3.57	57.0	38.7	12.5	1.4	3.3	46.3	3.61	58.6	41.6	12.8	3.5	8.0	47.5	3.65	59.9	43.4	13.0	4.7	10.9
				60	50.7	3.61	63.0	46.8	14.0	1.4	3.2	52.3	3.65	64.8	50.3	14.3	3.3	7.7	53.7	3.68	66.3	52.6	14.6	4.5	10.5
	7.5	0.9	2.1	70	56.6	3.65	69.0	54.9	15.5	1.3	3.0	58.4	3.69	70.9	59.1	15.8	3.2	7.4	59.9	3.72	72.6	61.8	16.1	4.4	10.1
				80	59.6	3.73	72.4	63.4	16.0	1.2	2.9	61.5	3.77	74.4	68.2	16.3	3.1	7.1	63.1	3.81	76.1	71.3	16.6	4.3	9.8
				90	62.7	3.82	75.7	71.9	16.4	1.2	2.7	64.7	3.86	77.9	77.3	16.8	3.0	6.9	66.4	3.90	79.7	80.9	17.0	4.1	9.6
				50	45.9	3.61	58.2	38.6	12.7	1.4	3.3	47.4	3.65	59.8	41.5	13.0	3.5	8.0	48.6	3.68	61.2	43.4	13.2	4.8	11.0
				60	51.8	3.65	64.3	46.7	14.2	1.4	3.2	53.5	3.68	66.0	50.2	14.5	3.3	7.7	54.9	3.72	67.6	52.5	14.7	4.6	10.6
90	11.25	2.7	6.1	70	57.7	3.69	70.3	54.8	15.7	1.3	3.0	59.6	3.72	72.3	58.9	16.0	3.2	7.4	61.1	3.76	73.9	61.6	16.2	4.4	10.2
				80	60.7	3.77	73.6	63.2	16.1	1.2	2.9	62.6	3.81	75.7	68.0	16.4	3.1	7.1	64.3	3.85	77.4	71.1	16.7	4.3	9.9
				90	63.7	3.86	76.9	71.7	16.5	1.2	2.7	65.7	3.90	79.0	77.1	16.9	3.0	6.9	67.4	3.94	80.9	80.6	17.1	4.1	9.6
				50	46.5	3.65	59.0	38.1	12.8	1.4	3.3	48.6	3.68	61.1	41.4	13.2	3.5	8.0	49.5	3.72	62.2	43.3	13.3	4.7	10.9
				60	52.4	3.68	64.9	46.2	14.2	1.4	3.2	54.2	3.72	66.9	50.1	14.6	3.3	7.7	55.8	3.76	68.6	52.4	14.8	4.6	10.5
	15.0	5.0	11.6	70	58.2	3.72	70.9	54.3	15.6	1.3	3.0	59.8	3.76	72.7	58.7	15.9	3.2	7.4	62.0	3.80	75.0	61.5	16.3	4.4	10.1
				80	61.6	3.81	74.6	62.9	16.2	1.2	2.9	63.4	3.85	76.6	67.8	16.5	3.1	7.1	65.8	3.89	79.0	70.8	16.9	4.3	9.8
				90	65.1	3.90	78.4	71.6	16.7	1.2	2.7	67.0	3.94	80.5	77.0	17.0	3.0	6.9	69.5	3.98	83.1	80.2	17.5	4.1	9.5
				50	39.8	4.46	55.0	39.9	8.9	1.4	3.3	41.3	4.50	56.7	42.5	9.2	3.5	8.0	41.7	4.55	57.3	44.1	9.2	4.7	10.9
				60	45.8	4.54	61.3	48.2	10.1	1.4	3.2	47.5	4.58	63.1	51.2	10.4	3.3	7.7	48.0	4.63	63.8	53.2	10.4	4.5	10.4
	7.5	0.8	1.8	70	51.8	4.62	67.5	56.4	11.2	1.3	3.0	53.7	4.66	69.6	60.0	11.5	3.2	7.4	54.3	4.71	70.4	62.4	11.5	4.3	10.0
				80	56.4	4.69	72.4	64.9	12.0	1.2	2.9	58.5	4.74	74.7	69.0	12.3	3.1	7.1	59.1	4.79	75.5	71.7	12.3	4.2	9.8
				90	61.0	4.77	77.3	73.4	12.8	1.2	2.7	63.3	4.82	79.7	78.0	13.1	3.0	6.9	64.0	4.87	80.6	81.1	13.1	4.2	9.6
				50	40.6	4.50	56.0	39.9	9.0	1.4	3.3	42.2	4.55	57.7	42.4	9.3	3.5	8.0	42.6	4.60	58.3	44.1	9.3	4.8	11.0
				60	47.3	4.58	62.9	48.1	10.3	1.4	3.2	49.0	4.63	64.8	51.2	10.6	3.3	7.7	49.6	4.68	65.5	53.2	10.6	4.6	10.5
110	11.25	2.4	5.6	70	53.9	4.66	69.8	56.3	11.6	1.3	3.0	55.9	4.71	72.0	59.9	11.9	3.2	7.4	56.5	4.76	72.7	62.2	11.9	4.4	10.1
				80	57.9	4.74	74.0	64.7	12.2	1.2	2.9	60.0	4.79	76.4	68.8	12.5	3.1	7.1	60.7	4.84	77.2	71.5	12.5	4.2	9.8
				90	61.8	4.82	78.3	73.1	12.8	1.2	2.7	64.1	4.87	80.8	77.7	13.2	3.0	6.9	64.8	4.92	81.6	80.8	13.2	4.1	9.5
				50	41.5	4.55	57.1	39.4	9.1	1.4	3.3	42.3	4.60	58.0	42.4	9.2	3.5	8.0	43.8	4.64	59.7	44.0	9.4	4.7	10.8
				60	47.6	4.63	63.4	47.4	10.3	1.4	3.2	48.5	4.68	64.5	51.1	10.4	3.3	7.7	50.7	4.72	66.8	53.1	10.7	4.5	10.5
	15.0	4.6	10.7	70	53.7	4.71	69.8	55.3	11.4	1.3	3.0	54.7	4.76	70.9	59.9	11.5	3.2	7.4	57.6	4.80	74.0	62.2	12.0	4.4	10.2
				80	58.3	4.79	74.6	64.2	12.2	1.2	2.9	59.7	4.84	76.2	68.7	12.3	3.1	7.1	61.7	4.89	78.4	71.4	12.6	4.3	9.8
				90	62.8	4.87	79.4	73.0	12.9	1.2	2.7	64.8	4.92	81.6	77.6	13.2	3.0	6.9	65.8	4.97	82.8	80.7	13.2	4.1	9.5
				50	37.0	5.04	54.2	40.3	7.3	1.4	3.3	38.5	5.09	55.9	43.2	7.6	3.5	8.0	39.3	5.14	56.8	44.7	7.6	4.7	10.9
				60	42.7	5.13	60.2	48.6	8.3	1.4	3.2	44.4	5.18	62.1	52.0	8.6	3.3	7.7	45.3	5.23	63.2	53.8	8.7	4.5	10.5
	7.5	0.7	1.7	70	48.4	5.21	66.2	56.9	9.3	1.3	3.0	50.4	5.27	68.3	60.8	9.6	3.2	7.4	51.4	5.32	69.5	62.9	9.7	4.3	10.0
				80	53.0	5.31	71.1	65.2	10.0	1.2	2.9	55.1	5.36	73.4	69.7	10.3	3.1	7.1	56.2	5.42	74.7	72.1	10.4	4.2	9.7
				90	57.5	5.40	76.0	73.5	10.6	1.2	2.7	59.9	5.46	78.5	78.6	11.0	3.0	6.9	61.1	5.51	79.9	81.3	11.1	4.1	9.4
				50	37.2	5.09	54.6	40.3	7.3	1.4	3.3	38.8	5.14	56.3	43.1	7.5	3.5	8.0	39.6	5.19	57.3	44.6	7.6	4.8	11.1
				60	43.2	5.18	60.8	48.5	8.3	1.4	3.2	44.9	5.23	62.8	51.9	8.6	3.3	7.7	45.8	5.28	63.8	53.7	8.7	4.6	10.6
120	11.25	2.4	5.5	70	49.1	5.27	67.0	56.7	9.3	1.3	3.0	51.1	5.32	69.2	60.6	9.6	3.2	7.4	52.1	5.37	70.4	62.7	9.7	4.4	10.1
				80	53.6	5.36	71.9	65.0	10.0	1.2	2.9	55.8	5.42	74.3	69.6	10.3	3.1	7.1	57.0	5.47	75.6	72.0	10.4	4.2	9.8
				90	58.2	5.46	76.9	73.4	10.7	1.2	2.7	60.6	5.51	79.4	78.5	11.0	3.0	6.9	61.8	5.57	80.9	81.3	11.1	4.1	9.5
				50	38.5	5.14	56.0	40.0	7.5	1.4	3.3	40.1	5.19	57.8	42.9	7.7	3.5	8.0	40.8	5.25	58.7	44.5	7.8	4.7	11.0
				60	44.4	5.23	62.2	48.2	8.5	1.4	3.2	46.4	5.28	64.4	51.7	8.8	3.3	7.7	47.3	5.34	65.5	53.6	8.9	4.6	10.5
	15.0	4.5	10.3	70	50.3	5.32	68.4	56.5	9.5	1.3	3.0	52.7	5.37	71.1	60.5	9.8	3.2	7.4	53.8	5.43	72.3	62.6	9.9	4.4	10.1
				80	54.9	5.42	73.4	64.9	10.1	1.2	2.9	57.5	5.47	76.2	69.5	10.5	3.1	7.1	58.6	5.53	77.5	71.9	10.6	4.2	9.8
				90	59.6	5.51	78.4	73.3	10.8	1.2	2.7	62.3	5.57	81.3	78.5	11.2	3.0	6.9	63.4	5.63	82.6	81.2	11.3	4.1	9.5

Table B.7 Continued - Submittal data for ClimateMaster TMW060 (60Hz I-P, HFC-410A) for a range of operating temperatures in heating mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 7.5 GPM							Flow 11.25 GPM							Flow 15.0 GPM						
	GPM	WPD			HC Mbtuh	Power kW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power kW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power kW	HE Mbtuh	LWT °F	COP	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
20	15.0	7.3	16.9	60	41.1	2.43	32.8	71.5	5.0	1.4	3.2	41.3	2.38	33.2	67.4	5.1	3.3	7.7	41.5	2.33	33.5	65.3	5.2	6.0	13.8
				80	40.5	3.17	29.6	91.2	3.7	1.2	2.9	40.6	3.11	30.0	87.2	3.8	3.1	7.1	40.7	3.05	30.3	85.3	3.9	5.6	13.0
				100	39.7	4.11	25.6	110.8	2.8	1.1	2.6	39.7	4.03	25.9	106.9	2.9	2.9	6.7	39.7	3.95	26.2	105.1	2.9	5.3	12.3
30	7.5	1.5	3.5	60	47.8	2.52	39.2	73.3	5.6	1.4	3.2	48.0	2.47	39.6	68.6	5.7	3.3	7.7	48.3	2.42	40.0	66.3	5.8	6.0	13.8
				80	46.9	3.28	35.7	92.9	4.2	1.2	2.9	47.1	3.21	36.1	88.4	4.3	3.1	7.1	47.2	3.15	36.5	86.1	4.4	5.6	13.0
				100	45.8	4.22	31.4	112.4	3.2	1.1	2.6	45.9	4.14	31.8	108.1	3.3	2.9	6.7	45.9	4.05	32.1	105.9	3.3	5.3	12.3
				120	44.6	5.36	26.3	131.9	2.4	1.1	2.4	44.5	5.25	26.6	127.7	2.5	2.8	6.4	44.4	5.14	26.9	125.7	2.5	5.1	11.7
	11.25	4.0	9.2	60	50.0	2.56	41.3	73.6	5.7	1.4	3.2	50.3	2.51	41.7	68.9	5.9	3.3	7.7	50.5	2.46	42.1	66.6	6.0	6.0	13.8
				80	49.0	3.33	37.6	93.3	4.3	1.2	2.9	49.1	3.26	38.0	88.7	4.4	3.1	7.1	49.3	3.20	38.4	86.5	4.5	5.6	13.0
				100	47.8	4.29	33.2	112.8	3.3	1.1	2.6	47.9	4.21	33.5	108.4	3.3	2.9	6.7	47.9	4.12	33.9	106.2	3.4	5.3	12.3
				120	46.6	5.45	28.0	132.1	2.5	1.1	2.4	46.5	5.34	28.3	128.0	2.6	2.8	6.4	46.4	5.23	28.6	125.9	2.6	5.1	11.7
	15.0	6.9	15.9	60	52.0	2.61	43.1	73.9	5.8	1.4	3.2	52.2	2.55	43.5	69.1	6.0	3.3	7.7	52.5	2.50	43.9	66.8	6.1	6.0	13.8
				80	50.9	3.39	39.3	93.4	4.4	1.2	2.9	51.1	3.32	39.7	88.9	4.5	3.1	7.1	51.2	3.25	40.1	86.6	4.6	5.6	13.0
				100	49.6	4.36	34.7	112.9	3.3	1.1	2.6	49.7	4.28	35.1	108.6	3.4	2.9	6.7	49.7	4.19	35.4	106.4	3.5	5.3	12.3
				120	48.1	5.54	29.2	132.3	2.5	1.1	2.4	48.0	5.43	29.5	128.2	2.6	2.8	6.4	47.9	5.32	29.8	126.1	2.6	5.1	11.7
40	7.5	1.4	3.2	60	54.4	2.61	45.5	75.0	6.1	1.4	3.2	54.7	2.56	46.0	69.7	6.3	3.3	7.7	55.1	2.51	46.5	67.2	6.4	6.0	13.8
				80	53.4	3.38	41.8	94.6	4.6	1.2	2.9	53.6	3.31	42.3	89.6	4.7	3.1	7.1	53.8	3.25	42.7	87.0	4.9	5.6	13.0
				100	52.0	4.33	37.2	114.0	3.5	1.1	2.6	52.1	4.24	37.6	109.2	3.6	2.9	6.7	52.2	4.16	38.0	106.7	3.7	5.3	12.3
				120	50.4	5.46	31.8	133.4	2.7	1.1	2.4	50.3	5.35	32.1	128.7	2.8	2.8	6.4	50.3	5.24	32.4	126.4	2.8	5.1	11.7
	11.25	3.7	8.5	60	57.4	2.65	48.3	75.5	6.4	1.4	3.2	57.7	2.59	48.8	70.1	6.5	3.3	7.7	58.0	2.54	49.3	67.5	6.7	6.0	13.8
				80	55.9	3.42	44.2	95.1	4.8	1.2	2.9	56.1	3.36	44.7	90.0	4.9	3.1	7.1	56.4	3.29	45.1	87.4	5.0	5.6	13.0
				100	54.3	4.38	39.4	114.5	3.6	1.1	2.6	54.4	4.30	39.8	109.7	3.7	2.9	6.7	54.5	4.21	40.2	107.1	3.8	5.3	12.3
				120	52.6	5.53	33.7	133.8	2.8	1.1	2.4	52.6	5.42	34.1	129.1	2.8	2.8	6.4	52.5	5.31	34.4	126.8	2.9	5.1	11.7
	15.0	6.5	15.1	60	59.2	2.68	50.1	75.9	6.5	1.4	3.2	59.6	2.63	50.6	70.5	6.6	3.3	7.7	59.9	2.58	51.1	67.9	6.8	6.0	13.8
				80	57.8	3.47	46.0	95.3	4.9	1.2	2.9	58.0	3.40	46.4	90.3	5.0	3.1	7.1	58.3	3.33	46.9	87.6	5.1	5.6	13.0
				100	56.1	4.44	40.9	114.7	3.7	1.1	2.6	56.2	4.35	41.3	109.9	3.8	2.9	6.7	56.3	4.27	41.7	107.3	3.9	5.3	12.3
				120	54.0	5.60	34.9	134.0	2.8	1.1	2.4	54.0	5.49	35.2	129.3	2.9	2.8	6.4	54.0	5.38	35.6	127.0	2.9	5.1	11.7
50	7.5	1.3	2.9	60	61.1	2.70	51.9	76.8	6.6	1.4	3.2	61.5	2.65	52.4	70.8	6.8	3.3	7.7	61.8	2.60	53.0	68.1	7.0	6.0	13.8
				80	59.8	3.48	47.9	96.3	5.0	1.2	2.9	60.1	3.41	48.4	90.8	5.2	3.1	7.1	60.3	3.34	48.9	87.8	5.3	5.6	13.0
				100	58.2	4.43	43.0	115.6	3.8	1.1	2.6	58.3	4.34	43.5	110.4	3.9	2.9	6.7	58.5	4.26	43.9	107.5	4.0	5.3	12.3
				120	56.2	5.55	37.2	134.9	3.0	1.1	2.4	56.2	5.44	37.6	129.7	3.0	2.8	6.4	56.2	5.33	38.0	127.2	3.1	5.1	11.7
				130	Operation not recommended							55.2	6.16	34.2	139.8	2.6	2.7	6.2	55.1	6.03	34.5	137.2	2.7	5.0	11.5
	11.25	3.4	7.9	60	64.7	2.73	55.4	77.4	6.9	1.4	3.2	65.1	2.68	56.0	71.3	7.1	3.3	7.7	65.5	2.62	56.5	68.5	7.3	6.0	13.8
				80	62.8	3.52	50.8	96.9	5.2	1.2	2.9	63.1	3.45	51.4	91.3	5.4	3.1	7.1	63.4	3.38	51.9	88.3	5.5	5.6	13.0
				100	60.8	4.48	45.5	116.2	4.0	1.1	2.6	61.0	4.39	46.0	110.9	4.1	2.9	6.7	61.1	4.30	46.5	108.0	4.2	5.3	12.3
				120	58.6	5.61	39.4	135.4	3.1	1.1	2.4	58.6	5.50	39.8	130.2	3.1	2.8	6.4	58.6	5.39	40.2	127.7	3.2	5.1	11.7
				130								57.9	6.22	36.7	139.9	2.7	2.7	6.2	57.8	6.09	37.1	137.3	2.8	5.0	11.5
	15.0	6.2	14.2	60	66.5	2.76	57.1	78.0	7.1	1.4	3.2	66.9	2.70	57.7	71.9	7.3	3.3	7.7	67.3	2.65	58.3	69.0	7.4	6.0	13.8
				80	64.7	3.55	52.6	97.2	5.3	1.2	2.9	65.0	3.48	53.1	91.6	5.5	3.1	7.1	65.3	3.41	53.6	88.6	5.6	5.6	13.0
				100	62.5	4.52	47.1	116.4	4.1	1.1	2.6	62.7	4.43	47.6	111.1	4.1	2.9	6.7	62.9	4.34	48.0	108.2	4.2	5.3	12.3
				120	60.0	5.67	40.6	135.6	3.1	1.1	2.4	60.0	5.55	41.0	130.5	3.2	2.8	6.4	60.0	5.44	41.4	127.9	3.2	5.1	11.7
				130								58.8	6.28	37.3	140.3	2.7	2.7	6.2	58.7	6.15	37.7	137.7	2.8	5.0	11.5

Table B.7 Continued - Submittal data for ClimateMaster TMW060 (60Hz I-P, HFC-410A) for a range of operating temperatures in heating mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 7.5 GPM							Flow 11.25 GPM							Flow 15.0 GPM						
	GPM	WPD PSI	WPD FT		HC Mbtuh	Power kW	HE Mbtuh	LWT °F	COP	WPD PSI	WPD FT	HC Mbtuh	Power kW	HE Mbtuh	LWT °F	COP	WPD PSI	WPD FT	HC Mbtuh	Power kW	HE Mbtuh	LWT °F	COP	WPD PSI	WPD FT
60	7.5	1.2	2.7	60	64.9	2.76	55.5	78.5	6.9	1.4	3.2	65.2	2.70	56.0	71.7	7.1	3.3	7.7	65.6	2.65	56.6	68.6	7.3	6.0	13.8
				80	64.8	3.54	52.7	98.1	5.4	1.2	2.9	65.1	3.47	53.3	91.8	5.5	3.1	7.1	65.4	3.40	53.8	88.6	5.6	5.6	13.0
				100	63.7	4.49	48.3	117.6	4.2	1.1	2.6	63.9	4.40	48.8	111.5	4.3	2.9	6.7	64.1	4.31	49.4	108.4	4.4	5.3	12.3
				120	61.4	5.60	42.3	136.7	3.2	1.1	2.4	61.5	5.48	42.8	130.9	3.3	2.8	6.4	61.6	5.37	43.2	128.0	3.4	5.1	11.7
				130	Operation not recommended							60.2	6.21	39.1	140.8	2.8	2.7	6.2	60.0	6.02	39.5	137.9	2.9	5.0	11.5
	11.25	3.2	7.3	60	67.7	2.78	58.2	79.0	7.1	1.4	3.2	68.1	2.73	58.8	72.2	7.3	3.3	7.7	68.5	2.67	59.4	69.1	7.5	6.0	13.8
				80	67.7	3.58	55.5	98.7	5.5	1.2	2.9	68.0	3.51	56.0	92.3	5.7	3.1	7.1	68.3	3.44	56.6	89.1	5.8	5.6	13.0
				100	66.4	4.54	50.9	118.1	4.3	1.1	2.6	66.6	4.45	51.5	112.0	4.4	2.9	6.7	66.9	4.36	52.0	108.9	4.5	5.3	12.3
				120	64.0	5.67	44.6	137.2	3.3	1.1	2.4	64.1	5.56	45.1	131.3	3.4	2.8	6.4	64.2	5.45	45.6	128.5	3.5	5.1	11.7
				130								63.1	6.27	41.7	141.0	3.0	2.7	6.2	62.9	6.08	42.2	138.1	3.0	5.0	11.5
	15.0	5.8	13.5	60	70.0	2.81	60.4	79.4	7.3	1.4	3.2	70.4	2.76	61.0	72.6	7.5	3.3	7.7	70.8	2.70	61.6	69.5	7.7	6.0	13.8
				80	70.0	3.62	57.7	99.0	5.7	1.2	2.9	70.4	3.54	58.3	92.6	5.8	3.1	7.1	70.7	3.47	58.9	89.4	6.0	5.6	13.0
				100	68.8	4.60	53.1	118.3	4.4	1.1	2.6	69.0	4.50	53.6	112.2	4.5	2.9	6.7	69.2	4.41	54.2	109.1	4.6	5.3	12.3
				120	66.2	5.75	46.6	137.4	3.4	1.1	2.4	66.3	5.63	47.1	131.6	3.4	2.8	6.4	66.4	5.52	47.5	128.7	3.5	5.1	11.7
				130															64.6	6.14	43.6	138.4	3.1	5.0	11.5
70	7.5	1.1	2.5	60	68.6	2.81	59.0	80.1	7.2	1.4	3.2	69.0	2.76	59.6	72.6	7.3	3.3	7.7	69.5	2.70	60.2	69.2	7.5	6.0	13.8
				80	69.8	3.61	57.5	100.0	5.7	1.2	2.9	70.2	3.53	58.1	92.8	5.8	3.1	7.1	70.5	3.46	58.7	89.4	6.0	5.6	13.0
				100	69.2	4.55	53.6	119.5	4.5	1.1	2.6	69.4	4.46	54.2	112.6	4.6	2.9	6.7	69.7	4.37	54.8	109.3	4.7	5.3	12.3
				120	66.7	5.64	47.4	138.5	3.5	1.1	2.4	66.8	5.52	47.9	132.0	3.5	2.8	6.4	66.9	5.41	48.5	128.9	3.6	5.1	11.7
				130															65.0	6.01	44.5	138.6	3.2	5.0	11.5
	11.25	3.0	6.9	60	70.7	2.84	61.0	80.7	7.3	1.4	3.2	71.2	2.78	61.7	73.2	7.5	3.3	7.7	71.6	2.73	62.3	69.7	7.7	6.0	13.8
				80	72.5	3.64	60.1	100.5	5.8	1.2	2.9	72.9	3.57	60.7	93.3	6.0	3.1	7.1	73.2	3.50	61.3	89.9	6.1	5.6	13.0
				100	72.1	4.61	56.3	119.9	4.6	1.1	2.6	72.3	4.52	56.9	113.1	4.7	2.9	6.7	72.6	4.43	57.5	109.7	4.8	5.3	12.3
				120	69.4	5.73	49.9	139.0	3.5	1.1	2.4	69.6	5.62	50.4	132.4	3.6	2.8	6.4	69.7	5.51	50.9	129.3	3.7	5.1	11.7
				130															68.0	6.07	47.3	138.9	3.3	5.0	11.5
	15.0	5.5	12.8	60	73.5	2.87	63.7	80.9	7.5	1.4	3.2	73.9	2.81	64.3	73.4	7.7	3.3	7.7	74.4	2.75	65.0	70.0	7.9	6.0	13.8
				80	75.4	3.68	62.8	100.7	6.0	1.2	2.9	75.8	3.61	63.5	93.5	6.2	3.1	7.1	76.2	3.53	64.1	90.1	6.3	5.6	13.0
				100	75.1	4.67	59.1	120.2	4.7	1.1	2.6	75.3	4.57	59.7	113.3	4.8	2.9	6.7	75.6	4.48	60.3	109.9	4.9	5.3	12.3
				120	72.5	5.83	52.6	139.2	3.6	1.1	2.4	72.6	5.71	53.1	132.7	3.7	2.8	6.4	72.7	5.60	53.6	129.5	3.8	5.1	11.7
				130															70.4	6.13	49.5	139.2	3.4	5.0	11.5
80	7.5	1.0	2.3	60	72.4	2.87	62.6	81.7	7.4	1.4	3.2	72.8	2.81	63.2	73.5	7.6	3.3	7.7	73.3	2.75	63.9	69.8	7.8	6.0	13.8
				80	74.8	3.67	62.3	101.8	6.0	1.2	2.9	75.2	3.60	62.9	93.9	6.1	3.1	7.1	75.6	3.52	63.6	90.2	6.3	5.6	13.0
				100	74.7	4.61	58.9	121.4	4.8	1.1	2.6	75.0	4.51	59.6	113.8	4.9	2.9	6.7	75.3	4.42	60.2	110.2	5.0	5.3	12.3
				120	71.9	5.68	52.5	140.4	3.7	1.1	2.4	72.1	5.56	53.1	133.2	3.8	2.8	6.4	72.3	5.45	53.7	129.8	3.9	5.1	11.7
				130															69.9	6.00	49.4	139.4	3.4	5.0	11.5
	11.25	2.8	6.5	60	73.7	2.89	63.9	82.3	7.5	1.4	3.2	74.2	2.84	64.5	74.1	7.7	3.3	7.7	74.7	2.78	65.2	70.3	7.9	6.0	13.8
				80	77.3	3.71	64.7	102.3	6.1	1.2	2.9	77.7	3.63	65.3	94.3	6.3	3.1	7.1	78.2	3.56	66.0	90.6	6.4	5.6	13.0
				100	77.7	4.67	61.8	121.8	4.9	1.1	2.6	78.0	4.58	62.4	114.2	5.0	2.9	6.7	78.4	4.49	63.0	110.6	5.1	5.3	12.3
				120	74.8	5.79	55.1	140.7	3.8	1.1	2.4	75.0	5.68	55.7	133.5	3.9	2.8	6.4	75.2	5.56	56.2	130.1	4.0	5.1	11.7
				130															73.1	6.06	52.4	139.7	3.5	5.0	11.5
	15.0	5.3	12.1	60	76.9	2.92	67.0	82.4	7.7	1.4	3.2	77.4	2.87	67.6	74.2	7.9	3.3	7.7	77.9	2.81	68.3	70.4	8.1	6.0	13.8
				80	80.7	3.74	68.0	102.5	6.3	1.2	2.9	81.2	3.67	68.7	94.5	6.5	3.1	7.1	81.6	3.60	69.3	90.8	6.7	5.6	13.0
				100	81.3	4.74	65.2	122.0	5.0	1.1	2.6	81.7	4.64	65.8	114.4	5.2	2.9	6.7	82.0	4.55	66.5	110.8	5.3	5.3	12.3
				120	78.7	5.91	58.5	141.0	3.9	1.1	2.4	78.9	5.79	59.1	133.8	4.0	2.8	6.4	79.1	5.68	59.7	130.4	4.1	5.1	11.7
				130															76.3	6.12	55.4	139.9	3.6	5.0	11.5

Table B.8 - Summary of performance data for ClimateMaster TMW340 (60Hz I-P, HFC-410A) for one operating temperature in both cooling and heating mode from submittal data (ClimateMaster, 2015; 2016).

Commercial (Mid)	
C. Mechanical Equipment Selection - Tranquility Modular Water-to-Water (TMW) Size 340	
Heat Pump Brand/Model	ClimateMaster/TMW340 Large Series
Heat Pump Tonnage - (Tons)	28
Heat Pump Coefficient of Performance (COP_D) in Heating Mode - (-)	3.3
Source Entering Water Temperature ($EWT_{S,H}$) in Heating Mode - (˚F)	30
Source Leaving Water Temperature ($LWT_{S,H}$) in Heating Mode - (˚F)	25.6
Source Flow Rate of Heat Pump - (GPM_S)	70
Load Flow Rate of Heat Pump - (GPM_L)	70
Density (ρ_{fluid}) of Heat Exchanger Fluid - (kg/m^3)	1060
Load Entering Water Temperature ($EWT_{L,H}$) in Heating Mode - (˚F)	100
Load Leaving Water Temperature ($LWT_{L,H}$) in Heating Mode - (˚F)	106.3
Electric Consumption of Heat Pump Unit in Heating Mode - (kW)	19.72
Heating Capacity (HC_{HP}) of the Heat Pump Unit in Heating Mode - (Btu/hr)	221300
Heat of Extraction (HE_{HP}) of the Heat Pump in Heating Mode - (Btu/hr)	154100
Heat Pump Coefficient of Performance (EER_D) in Cooling Mode - (-)	13.3
Source Entering Water Temperature ($EWT_{S,C}$) in Cooling Mode - (˚F)	90
Source Leaving Water Temperature ($LWT_{S,C}$)in Cooling Mode - (˚F)	98.8
Load Entering Water Temperature ($EWT_{L,C}$) in Cooling Mode - (˚F)	50
Load Leaving Water Temperature ($LWT_{L,C}$) in Cooling Mode - (˚F)	43
Electric Consumption of Heat Pump Unit in Cooling Mode - (kW)	18.36
Cooling Capacity (CC_{HP}) of the Heat Pump Unit in Cooling Mode - (Btu/hr)	244500
Heat of Rejection (HR_{HP}) of the Heat Pump in Cooling Mode - (Btu/hr)	307200

Appendix B: Supporting Documentation for Chapter 6

Table B.9 - Submittal data for ClimateMaster TMW340 (60Hz I-P, HFC-410A) for a range of operating temperatures in cooling mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 35.0 GPM							Flow 53.0 GPM							Flow 70.0 GPM						
	GPM	WPD			TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD		TC Mbtuh	Power kW	HR Mbtuh	LWT °F	EER	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
50	35.0	1.19	2.75	50	258.7	13.68	305.4	35.2	18.6	1.2	2.7	271.2	13.86	318.5	39.8	19.6	3.6	8.3	277.3	13.94	324.9	42.1	19.9	6.50	15.00
				60	282.0	13.81	329.1	43.9	20.1	1.1	2.5	294.1	13.92	341.6	48.9	21.1	3.44	7.94	299.9	13.97	347.5	51.4	21.5	6.18	14.28
				70	302.7	13.99	350.4	52.7	21.3	1.0	2.3	313.9	14.09	362.0	58.2	22.3	3.29	7.60	319.0	14.14	367.3	60.9	22.6	5.91	13.64
				80	320.5	14.15	368.8	61.7	22.4	0.9	2.2	330.2	14.24	378.8	67.5	23.2	3.15	7.28	334.5	14.28	383.2	70.4	23.4	5.67	13.09
				90	335.0	14.28	383.8	70.9	23.3	0.9	2.0	342.7	14.35	391.6	77.1	23.9	3.02	6.97	345.8	14.38	394.8	80.1	24.0	5.47	12.64
	53.0	3.59	8.30	50	262.2	12.69	305.5	35.0	20.2	1.2	2.7	275.0	12.76	318.5	39.6	21.5	3.6	8.3	281.1	12.80	324.8	42.0	22.0	6.50	15.00
				60	285.4	12.83	329.2	43.7	21.9	1.1	2.5	297.6	12.90	341.6	48.8	23.1	3.44	7.94	303.3	12.93	347.4	51.3	23.4	6.18	14.28
				70	305.8	12.95	350.0	52.5	23.3	1.0	2.3	316.8	13.01	361.2	58.0	24.3	3.29	7.60	321.9	13.04	366.4	60.8	24.7	5.91	13.64
				80	323.1	13.05	367.7	61.5	24.5	0.9	2.2	332.6	13.11	377.4	67.4	25.4	3.15	7.28	336.8	13.13	381.6	70.4	25.6	5.67	13.09
				90	337.3	13.14	382.1	70.7	25.5	0.9	2.0	344.8	13.18	389.8	77.0	26.2	3.02	6.97	347.9	13.20	392.9	80.1	26.4	5.47	12.64
	70.0	6.50	15.02	50	263.4	12.24	305.1	35.0	21.1	1.2	2.7	276.2	12.30	318.2	39.6	22.5	3.6	8.3	282.4	12.33	324.5	41.9	22.9	6.50	15.00
				60	286.7	12.35	328.9	43.6	22.8	1.1	2.5	298.9	12.41	341.2	48.7	24.1	3.44	7.94	304.6	12.43	347.0	51.3	24.5	6.18	14.28
				70	307.1	12.44	349.6	52.5	24.3	1.0	2.3	318.1	12.50	360.7	58.0	25.5	3.29	7.60	323.1	12.52	365.8	60.8	25.8	5.91	13.64
				80	324.3	12.52	367.1	61.5	25.6	0.9	2.2	333.7	12.57	376.6	67.4	26.6	3.15	7.28	337.8	12.59	380.8	70.3	26.8	5.67	13.09
				90	338.2	12.59	381.2	70.7	26.7	0.9	2.0	345.6	12.62	388.7	77.0	27.4	3.02	6.97	348.6	12.63	391.7	80.0	27.6	5.47	12.64
70	35.0	1.01	2.34	50	237.7	16.52	294.1	36.4	13.9	1.2	2.7	251.5	16.64	308.3	40.5	15.1	3.6	8.3	258.3	16.70	315.3	42.6	15.5	6.50	15.00
				60	265.3	16.76	322.5	44.8	15.4	1.1	2.5	279.0	16.88	336.6	49.5	16.5	3.44	7.94	285.6	16.94	343.4	51.8	16.9	6.18	14.28
				70	289.9	16.98	347.8	53.4	16.7	1.0	2.3	302.7	17.10	361.1	58.6	17.7	3.29	7.60	308.7	17.15	367.2	61.2	18.0	5.91	13.64
				80	311.0	17.17	369.6	62.2	17.8	0.9	2.2	322.2	17.27	381.1	67.8	18.7	3.15	7.28	327.1	17.32	386.2	70.7	18.9	5.67	13.09
				90	328.1	17.32	387.2	71.3	18.7	0.9	2.0	336.8	17.40	396.2	77.3	19.4	3.02	6.97	340.3	17.43	399.8	80.3	19.5	5.47	12.64
	53.0	3.29	7.60	50	244.7	15.68	298.2	36.0	15.1	1.2	2.7	258.4	15.76	312.2	40.2	16.4	3.6	8.3	265.2	15.80	319.1	42.4	16.8	6.50	15.00
				60	271.4	15.83	325.4	44.5	16.7	1.1	2.5	284.8	15.91	339.1	49.3	17.9	3.44	7.94	291.2	15.95	345.6	51.7	18.3	6.18	14.28
				70	294.9	15.97	349.4	53.1	18.1	1.0	2.3	307.3	16.04	362.1	58.4	19.2	3.29	7.60	313.0	16.08	367.9	61.1	19.5	5.91	13.64
				80	315.0	16.09	369.8	62.0	19.3	0.9	2.2	325.5	16.15	380.6	67.7	20.2	3.15	7.28	330.1	16.17	385.3	70.6	20.4	5.67	13.09
				90	330.9	16.18	386.1	71.1	20.2	0.9	2.0	338.9	16.23	394.2	77.2	20.9	3.02	6.97	341.9	16.24	397.4	80.2	21.1	5.47	12.64
	70.0	5.91	13.64	50	247.9	15.28	300.1	35.8	15.7	1.2	2.7	261.5	15.34	313.9	40.1	17.0	3.6	8.3	268.2	15.37	320.6	42.3	17.5	6.50	15.00
				60	274.0	15.39	326.5	44.3	17.4	1.1	2.5	287.3	15.45	340.0	49.2	18.6	3.44	7.94	293.6	15.48	346.4	51.6	19.0	6.18	14.28
				70	297.0	15.49	349.9	53.0	18.8	1.0	2.3	309.2	15.55	362.3	58.3	19.9	3.29	7.60	314.8	15.57	367.9	61.0	20.2	5.91	13.64
				80	316.6	15.58	369.7	61.9	20.0	0.9	2.2	326.9	15.62	380.2	67.7	20.9	3.15	7.28	331.4	15.64	384.8	70.5	21.2	5.67	13.09
				90	332.1	15.65	385.5	71.0	21.0	0.9	2.0	339.9	15.68	393.4	77.2	21.7	3.02	6.97	343.0	15.69	396.5	80.2	21.9	5.47	12.64
90	35.0	0.88	2.03	50	212.3	19.51	278.9	37.9	10.3	1.2	2.7	225.8	19.64	292.8	41.5	11.5	3.6	8.3	232.6	19.71	299.8	43.4	11.8	6.50	15.00
				60	242.3	19.80	309.9	46.2	11.7	1.1	2.5	256.2	19.94	324.3	50.3	12.8	3.44	7.94	263.1	20.01	331.4	52.5	13.1	6.18	14.28
				70	269.7	20.08	338.2	54.6	13.0	1.0	2.3	283.6	20.22	352.6	59.3	14.0	3.29	7.60	290.4	20.28	359.6	61.7	14.3	5.91	13.64
				80	294.5	20.32	363.8	63.2	14.1	0.9	2.2	308.0	20.46	377.8	68.4	15.1	3.15	7.28	314.4	20.53	384.5	71.0	15.3	5.67	13.09
				90	316.5	20.55	386.6	71.9	15.1	0.9	2.0	329.1	20.68	399.7	77.6	15.9	3.02	6.97	334.9	20.74	405.6	80.4	16.2	5.47	12.64
	53.0	3.02	6.97	50	219.5	18.66	283.1	37.5	11.2	1.2	2.7	233.7	18.75	297.6	41.2	12.5	3.6	8.3	240.8	18.79	304.9	43.1	12.8	6.50	15.00
				60	249.9	18.85	314.2	45.7	12.7	1.1	2.5	264.3	18.94	329.0	50.0	14.0	3.44	7.94	271.4	18.98	336.1	52.2	14.3	6.18	14.28
				70	277.2	19.02	342.1	54.2	14.1	1.0	2.3	291.2	19.10	356.4	59.0	15.2	3.29	7.60	297.9	19.15	363.2	61.5	15.6	5.91	13.64
				80	301.3	19.17	366.7	62.8	15.3	0.9	2.2	314.3	19.25	379.9	68.1	16.3	3.15	7.28	320.3	19.29	386.1	70.8	16.6	5.67	13.09
				90	321.9	19.30	387.7	71.6	16.3	0.9	2.0	333.3	19.37	399.4	77.4	17.2	3.02	6.97	338.4	19.40	404.6	80.3	17.4	5.47	12.64
	70.0	5.47	12.64	50	222.8	18.26	285.1	37.3	11.6	1.2	2.7	237.3	18.32	299.8	41.0	13.0	3.6	8.3	244.5	18.36	307.2	43.0	13.3	6.50	15.00
				60	253.4	18.40	316.2	45.5	13.2	1.1	2.5	268.0	18.47	331.0	49.9	14.5	3.44	7.94	275.1	18.50	338.2	52.1	14.9	6.18	14.28
				70	280.6	18.52	343.8	54.0	14.7	1.0	2.3	294.5	18.59	357.9	58.9	15.8	3.29	7.60	301.1	18.62	364.6	61.4	16.2	5.91	13.64
				80	304.2	18.63	367.7	62.6	15.9	0.9	2.2	316.8	18.69	380.6	68.0	16.9	3.15	7.28	322.5	18.72	386.4	70.8	17.2	5.67	13.09
				90	323.9	18.72	387.8	71.5	17.0	0.9	2.0	334.5	18.77	398.6	77.4	17.8	3.02	6.97	339.1	18.79	403.2	80.3	18.0	5.47	12.64
110	35.0	0.79	1.82	50	178.7	22.84	256.6	39.8	7.2	1.19	2.75	191.9	22.99	270.4	42.8	8.3	3.59	8.30	198.8	23.07	277.5	44.3	8.6	6.50	15.02
				60	213.9	23.25	293.2	47.8	8.6	1.10	2.53	229.0	23.42	308.9	51.4	9.8	3.44	7.94	236.6	23.51	316.8	53.2	10.1	6.18	14.28
				70	246.8	23.64	327.4	55.9	9.9	1.01	2.34	261.3	23.81	342.6	60.1	11.0	3.29	7.60	267.9	23.89	349.4	62.3	11.2	5.91	13.64
				80	273.2	23.95	354.9	64.4	11.0	0.94	2.17	Operation not recommended													
				90	Operation not recommended																				
	53.0	2.77	6.40	50	189.2	21.95	264.1	39.2	8.0	1.19	2.75	202.5	22.05	277.7	42.4	9.2	3.59	8.30	209.3	22.10	284.7	44.0	9.5	6.50	15.02
				60	222.5	22.19	298.2	47.3	9.4	1.10	2.53	237.0	22.30	313.1	51.1	10.6	3.44	7.94	244.3	22.35	320.6	53.0	10.9	6.18	14.28
				70	253.3	22.41	329.8	55.5	10.8	1.01	2.34	268.0	22.52	344.8	59.9	11.9	3.29	7.60	275.0	22.57	352.0	62.1	12.2	5.91	13.64
				80	280.4	22.61	357.6	64.0	11.9	0.94	2.17	293.5	22.71	371.0	68.9	12.9	3.15	7.28	299.3	22.75	376.9	71.4	13.2	5.67	13.09
				90	302.0	22.77	379.7	72.7	12.9	0.88	2.03	311.6	22.85	389.5	78.2	13.6	3.02	6.97	315.2	22.87	393.3	81.0	13.8	5.47	12.64
	70.0	5.20	12.02	50	193.7	21.53	267.2	38.9	8.4	1.19	2.75	207.2	21.60	280.9	42.2	9.6	3.59	8.30	214.1	21.63	287.9	43.9	9.9	6.50	15.02
				60	226.6	21.70	300.6	47.1	9.8	1.10	2.53	241.1	21.78	315.4	50.9	11.1	3.44	7.94	248.4	21.81	322.8	52.9	11.4	6.18	14.28
				70	256.9	21.86	331.5	55.3	11.2	1.01	2.34	271.6	21.94	346.5	59.7	12.4	3.29	7.60	278.8	21.98	353.8	62.0	12.7	5.91	13.64
				80	284.0	22.01	359.1	63.8	12.4	0.94	2.17	297.9	22.08	373.3	68.8	13.5	3.15	7.28	304.4	22.12	379.8	71.3	13.8	5.67	13.09
				90	307.1	22.13	382.6	72.5	13.5	0.88	2.03	318.9	22.19	394.6	78.0	14.4	3.02	6.97	324.0	22.22	399.8	80.7	14.6	5.47	12.64

Table B.9 Continued - Submittal data for ClimateMaster TMW340 (60Hz I-P, HFC-410A)for a range of operating temperatures in heating mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD																					
EWT °F	Flow			EWT °F	Flow 35.0 GPM							Flow 53.0 GPM							Flow 70.0 GPM						
	GPM	WPD			HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD		HC Mbtuh	Power KW	HE Mbtuh	LWT °F	COP	WPD	
		PSI	FT							PSI	FT						PSI	FT						PSI	FT
20	35.0	1.71	3.96	60	206.9	13.68	160.2	72	4.4	1.01	2.53	213.1	13.68	166.4	68.0	4.6	3.44	7.94	219.6	13.67	172.9	66.3	4.7	6.18	14.28
				80	190.2	16.96	132.4	91	3.3	0.94	2.17	195.3	16.96	137.5	87.4	3.4	3.15	7.28	200.7	16.95	142.9	85.7	3.5	5.67	13.09
	53.0	4.19	9.69	60	215.6	13.73	168.7	72	4.6	1.01	2.53	226.4	14.88	175.7	68.5	4.5	3.44	7.94	229.8	13.72	183.0	66.6	4.9	6.18	14.28
				80	197.7	17.02	139.6	91	3.4	0.94	2.17	203.4	17.01	145.3	87.7	3.5	3.15	7.28	209.4	17.01	151.4	86.0	3.6	5.67	13.09
	70.0	7.49	17.30	60	220.0	13.76	173.0	73	4.7	1.01	2.53	231.1	14.88	180.3	68.7	4.6	3.44	7.94	235.0	13.75	188.1	66.7	5.0	6.18	14.28
				80	201.4	17.04	143.3	92	3.5	0.94	2.17	207.4	17.04	149.3	87.8	3.6	3.15	7.28	213.8	17.03	155.7	86.1	3.7	5.67	13.09
				100	184.6	19.46	118.2	110.5	2.8	0.83	1.91	185.2	19.46	118.8	107.0	2.8	2.89	6.68	190.3	19.46	123.9	105.4	2.9	5.32	12.28
30	35.0	1.63	3.77	60	232.9	13.83	185.7	73	4.9	1.01	2.53	240.2	13.83	193.0	69.1	5.1	3.44	7.94	251.4	14.84	200.7	67.2	5.0	6.18	14.28
				80	217.1	17.16	158.5	92	3.7	0.94	2.17	223.3	17.15	164.7	88.4	3.8	3.15	7.28	229.8	17.14	171.3	86.6	3.9	5.67	13.09
				100	198.4	19.63	131.5	111.3	3.0	0.83	1.91	203.5	19.62	136.6	107.7	3.0	2.89	6.68	208.9	19.61	142.0	106.0	3.1	5.32	12.28
	53.0	4.03	9.31	60	242.3	13.89	194.9	74	5.1	1.01	2.53	253.8	14.90	203.0	69.6	5.0	3.44	7.94	262.2	14.85	211.5	67.5	5.2	6.18	14.28
				80	225.4	17.23	166.7	93	3.8	0.94	2.17	232.3	17.22	173.5	88.8	4.0	3.15	7.28	239.6	17.21	180.8	86.8	4.1	5.67	13.09
				100	205.5	19.69	138.3	111.7	3.1	0.83	1.91	211.1	19.69	144.0	108.0	3.1	2.89	6.68	217.2	19.68	150.0	106.2	3.2	5.32	12.28
				120	Operation not recommended														207.0	24.83	122.3	125.9	2.4	5.13	11.86
	70.0	7.18	16.58	60	246.9	13.92	199.4	74	5.2	1.01	2.53	258.8	14.91	207.9	69.8	5.1	3.44	7.94	267.6	14.85	216.9	67.6	5.3	6.18	14.28
				80	229.6	17.26	170.7	93	3.9	0.94	2.17	236.8	17.26	177.9	88.9	4.0	3.15	7.28	244.5	17.25	185.6	87.0	4.2	5.67	13.09
				100	214.3	19.72	147.0	112.2	3.2	0.83	1.91	215.0	19.72	147.7	108.1	3.2	2.89	6.68	221.3	19.72	154.1	106.3	3.3	5.32	12.28
				120								205.2	24.86	120.4	127.7	2.4	2.66	6.15	210.4	24.85	125.6	126.0	2.5	5.13	11.86
40	35.0	1.55	3.57	60	257.1	13.99	209.4	74.7	5.4	1.01	2.53	265.4	13.98	217.7	70.0	5.6	3.44	7.94	277.2	14.86	226.5	67.9	5.5	6.18	14.28
				80	242.3	17.37	183.1	93.8	4.1	0.94	2.17	249.5	17.36	190.3	89.4	4.2	3.15	7.28	257.1	17.35	197.9	87.3	4.3	5.67	13.09
				100	224.2	19.87	156.4	112.8	3.3	0.83	1.91	230.3	19.86	162.5	108.7	3.4	2.89	6.68	236.8	19.85	169.1	106.8	3.5	5.32	12.28
				120								222.6	24.97	137.4	128.4	2.6	2.66	6.15	228.1	24.96	142.9	126.5	2.7	5.13	11.86
	53.0	3.87	8.94	60	266.8	14.06	218.8	75.2	5.6	1.01	2.53	278.9	14.93	228.0	70.5	5.5	3.44	7.94	288.4	14.87	237.7	68.2	5.7	6.18	14.28
				80	251.3	17.45	191.7	94.4	4.2	0.94	2.17	259.2	17.44	199.7	89.8	4.4	3.15	7.28	267.7	17.44	208.2	87.6	4.5	5.67	13.09
				100	232.2	19.96	164.1	113.3	3.4	0.83	1.91	238.9	19.95	170.9	109.0	3.5	2.89	6.68	246.1	19.94	178.1	107.0	3.6	5.32	12.28
				120	224.1	25.02	138.7	132.8	2.6	0.76	1.75	229.8	25.02	144.4	128.7	2.7	2.66	6.15	235.9	25.01	150.5	126.7	2.8	5.13	11.86
	70.0	6.87	15.87	60	271.6	14.10	223.4	75.5	5.6	1.01	2.53	284.0	14.93	233.0	70.7	5.6	3.44	7.94	294.0	14.87	243.2	68.4	5.8	6.18	14.28
				80	255.7	17.49	196.0	94.6	4.3	0.94	2.17	264.1	17.49	204.4	90.0	4.4	3.15	7.28	272.9	17.48	213.3	87.8	4.6	5.67	13.09
				100	242.4	19.99	174.2	113.9	3.6	0.83	1.91	243.3	19.99	175.1	109.2	3.6	2.89	6.68	250.8	19.99	182.7	107.2	3.7	5.32	12.28
				120	227.4	25.05	141.9	133.0	2.7	0.76	1.75	233.4	25.05	148.0	128.8	2.7	2.66	6.15	239.8	25.04	154.4	126.9	2.8	5.13	11.86
50	35.0	1.19	2.75	60	279.4	14.17	231.1	76.0	5.8	1.01	2.53	288.7	14.15	240.4	70.9	6.0	3.44	7.94	301.0	14.88	250.2	68.6	5.9	6.18	14.28
				80	265.9	17.59	205.8	95.2	4.4	0.94	2.17	274.1	17.58	214.1	90.3	4.6	3.15	7.28	282.7	17.57	222.8	88.1	4.7	5.67	13.09
				100	248.8	20.14	180.1	114.2	3.6	0.83	1.91	255.9	20.12	187.3	109.7	3.7	2.89	6.68	263.4	20.11	194.8	107.5	3.8	5.32	12.28
				120	241.6	25.17	155.8	133.8	2.8	0.76	1.75	247.8	25.16	162.0	129.4	2.9	2.66	6.15	254.3	25.15	168.5	127.3	3.0	5.13	11.86
	53.0	3.59	8.30	60	289.1	14.25	240.5	76.5	5.9	1.01	2.53	301.6	14.95	250.6	71.4	5.9	3.44	7.94	312.2	14.89	261.4	68.9	6.1	6.18	14.28
				80	275.2	17.69	214.8	95.7	4.6	0.94	2.17	284.1	17.68	223.8	90.7	4.7	3.15	7.28	293.7	17.67	233.4	88.4	4.9	5.67	13.09
				100	257.5	20.23	188.5	114.7	3.7	0.83	1.91	265.3	20.22	196.3	110.0	3.8	2.89	6.68	273.7	20.21	204.7	107.8	4.0	5.32	12.28
				120	249.0	25.23	162.9	134.2	2.9	0.76	1.75	255.8	25.23	169.7	129.7	3.0	2.66	6.15	263.0	25.22	177.0	127.5	3.1	5.13	11.86
	70.0	6.50	15.02	60	293.8	14.29	245.0	76.8	6.0	1.01	2.53	306.6	14.95	255.6	71.6	6.0	3.44	7.94	317.7	14.89	266.9	69.1	6.3	6.18	14.28
				80	279.7	17.74	219.2	96.0	4.6	0.94	2.17	289.1	17.73	228.6	90.9	4.8	3.15	7.28	299.1	17.72	238.6	88.5	4.9	5.67	13.09
				100	269.1	20.28	199.9	115.4	3.9	0.83	1.91	270.1	20.28	200.9	110.2	3.9	2.89	6.68	278.8	20.27	209.6	108.0	4.0	5.32	12.28
				120	252.7	25.27	166.5	134.4	2.9	0.76	1.75	259.8	25.26	173.6	129.8	3.0	2.66	6.15	267.3	25.26	181.2	127.6	3.1	5.13	11.86
60	35.0	1.01	2.53	60	299.6	14.35	250.7	77.1	6.1	1.01	2.53	309.8	14.34	260.9	71.7	6.3	3.44	7.94	322.6	14.89	271.8	69.2	6.3	6.18	14.28
				80	287.6	17.83	226.8	96.4	4.7	0.94	2.17	296.8	17.82	236.0	91.2	4.9	3.15	7.28	306.5	17.80	245.7	88.8	5.1	5.67	13.09
				100	272.2	20.41	202.6	115.6	3.9	0.83	1.91	280.3	20.39	210.7	110.6	4.0	2.89	6.68	288.8	20.38	219.3	108.3	4.2	5.32	12.28
				120	264.5	25.39	177.8	135.1	3.1	0.76	1.75	271.6	25.38	185.0	130.2	3.1	2.66	6.15	279.1	25.36	192.5	128.0	3.2	5.13	11.86
	53.0	3.44	7.94	60	309.1	14.45	259.8	77.7	6.3	1.01	2.53	321.9	14.97	270.9	72.1	6.3	3.44	7.94	333.5	14.90	282.7	69.5	6.6	6.18	14.28
				80	297.0	17.94	235.8	97.0	4.9	0.94	2.17	307.0	17.93	245.8	91.6	5.0	3.15	7.28	317.6	17.92	256.4	89.1	5.2	5.67	13.09
				100	281.5	20.52	211.4	116.1	4.0	0.83	1.91	290.3	20.51	220.3	111.0	4.1	2.89	6.68	299.7	20.50	229.7	108.6	4.3	5.32	12.28
				120	272.3	25.47	185.4	135.6	3.1	0.76	1.75	280.1	25.46	193.2	130.6	3.2	2.66	6.15	288.3	25.46	201.5	128.2	3.3	5.13	11.86
	70.0	6.18	14.28	60	313.5	14.50	264.1	77.9	6.3	1.01	2.53	326.6	14.97	275.6	72.3	6.4	3.44	7.94	338.7	14.90	287.8	69.7	6.7	6.18	14.28
				80	301.5	18.00	240.1	97.2	4.9	0.94	2.17	311.9	17.99	250.5	91.8	5.1	3.15	7.28	323.0	17.98	261.6	89.2	5.3	5.67	13.09
				100	294.2	20.58	224.0	116.8	4.2	0.83	1.91	295.3	20.57	225.1	111.1	4.2	2.89	6.68	305.1	20.57	234.9	108.7	4.3	5.32	12.28
				120	276.2	25.52	189.1	135.8	3.2	0.76	1.75	284.3	25.51	197.2	130.7	3.3	2.66	6.15	292.9	25.50	205.9	128.4	3.4	5.13	11.86
70	35.0	1.01	2.34	60	317.8	14.55	268.2	78.2	6.4	1.01	2.53	328.9	14.53	279.3	72.4	6.6	3.44	7.94	342.0	14.91	291.1	69.8	6.7	6.18	14.28
				80	307.6	18.08	245.9	97.6	5.0	0.94	2.17	317.6	18.06	256.0	92.0	5.2	3.15	7.28	328.3	18.05	266.7	89.4	5.3	5.67	13.09
				100	294.4	20.69	223.8	116.8	4.2	0.83	1.91	303.4	20.68	232.8	111.4	4.3	2.89	6.68	312.9	20.66	242.4	108.9	4.4	5.32	12.28
				120	285.8	25.63	198.3	136.3	3.3	0.76	1.75	293.8	25.62	206.4	131.1	3.4	2.66	6.15	302.3	25.61	214.9	128.6	3.5	5.13	11.86
	53.0	3.29	7.60	60	326.7	14.66	276.6	78.7	6.5	1.01	2.53	339.7	14.98	288.6	72.8	6.6	3.44	7.94	352.2	14.91	301.3	70.1	6.9	6.18	14.28
				80	316.8	18.21	254.7	98.1	5.1	0.94	2.17	327.7	18.20	265.6	92.4	5.3	3.15	7.28	339.2	18.18	277.2	89.7	5.5	5.67	13.09
				100	304.0	20.83	232.9	117.4	4.3	0.83	1.91	313.8	20.82	242.8	111.8	4.4	2.89	6.68	324.2	20.80	253.2	109.3	4.6	5.32	12.28
				120	293.9	25.74	206.1	136.8	3.3	0.76	1.75	302.6	25.73	214.8	131.4	3.4	2.66	6.15	311.9	25.72	224.1	128.9	3.6	5.13	11.86
	70.0	5.91	13.64	60	330.8	14.72	280.6	78.9	6.6	1.01	2.53	344.0	14.99	292.9	73.0	6.7	3.44	7.94	356.9	14.92	306.0	70.2	7.0	6.18	14.28
				80	321.2	18.27	258.8	98.4	5.2	0.94	2.17	332.4	18.26	270.1	92.5	5.3	3.15	7.28	344.4	18.25	282.1	89.8	5.5	5.67	13.09
				100	317.7	20.89	246.4	118.2	4.5	0.83	1.91	318.9	20.89	247.7	112.0	4.5	2.89	6.68	329.8	20.88	258.6	109.4	4.6	5.32	12.28
				120	297.8	25.79	209.8	137.0	3.4	0.76	1.75	306.9	25.79	218.9	131.6	3.5	2.66	6.15	316.5	25.78	228.6	129.0	3.6	5.13	11.86

Table B.10 - Summary of performance data for ClimateMaster TMW600 Large Series (60Hz I-P, HFC-410A) for one operating temperature in both cooling and heating mode from submittal data (ClimateMaster, 2015; 2016).

Commercial (Large)	
C. Mechanical Equipment Selection - Tranquility Modular Water-to-Water (TMW) Size 600	
Heat Pump Brand/Model	ClimateMaster/TMW600 Large Series
Heat Pump Tonnage - (Tons)	50
Heat Pump Coefficient of Performance (COP_D) in Heating Mode - (-)	3.5
Source Entering Water Temperature ($EWT_{S,H}$) in Heating Mode - (˚F)	30
Source Leaving Water Temperature ($LWT_{S,H}$) in Heating Mode - (˚F)	25.1
Source Flow Rate of Heat Pump - (GPM_S)	150
Load Flow Rate of Heat Pump - (GPM_L)	150
Density (ρ_{fluid}) of Heat Exchanger Fluid - (kg/m^3)	1060
Load Entering Water Temperature ($EWT_{L,H}$) in Heating Mode - (˚F)	100
Load Leaving Water Temperature ($LWT_{L,H}$) in Heating Mode - (˚F)	106.9
Electric Consumption of Heat Pump Unit in Heating Mode - (kW)	42.43
Heating Capacity (HC_{HP}) of the Heat Pump Unit in Heating Mode - (Btu/hr)	513500
Heat of Extraction (HE_{HP}) of the Heat Pump in Heating Mode - (Btu/hr)	369000
Heat Pump Coefficient of Performance (EER_D) in Cooling Mode - (-)	14.2
Source Entering Water Temperature ($EWT_{S,C}$) in Cooling Mode - (˚F)	90
Source Leaving Water Temperature ($LWT_{S,C}$)in Cooling Mode - (˚F)	99.4
Load Entering Water Temperature ($EWT_{L,C}$) in Cooling Mode - (˚F)	50
Load Leaving Water Temperature ($LWT_{L,C}$) in Cooling Mode - (˚F)	42.5
Electric Consumption of Heat Pump Unit in Cooling Mode - (kW)	40.1
Cooling Capacity (CC_{HP}) of the Heat Pump Unit in Cooling Mode - (Btu/hr)	568900
Heat of Rejection (HR_{HP}) of the Heat Pump in Cooling Mode - (Btu/hr)	705300

Table B.11 - Submittal data for ClimateMaster TMW600 Large Series (60Hz I-P, HFC-410A) for a range of operating temperatures in cooling mode (ClimateMaster, 2015; 2016).

SOURCE				LOAD								SLWT	LOAD							SLWT	LOAD							SLWT
EWT	Flow			EWT	Flow 75 GPM							°F	Flow 113 GPM							°F	Flow 150 GPM							°F
°F	GPM	WPD PSI	WPD FT	°F	TC	kW	HR	LLWT	EER	WPD PSI	WPD FT		TC	kW	HR	LLWT	EER	WPD PSI	WPD FT		TC	kW	HR	LLWT	EER	WPD PSI	WPD FT	
60	75	1.7	4.0	40	506.2	30.6	610.3	26.6	16.5	1.7	3.9	76.2	528.3	30.9	633.4	30.7	17.1	3.6	8.3	76.8	538.9	31.1	644.6	32.9	17.3	6.3	14.5	77.1
				50	593.0	31.8	701.3	34.3	18.6	1.7	3.9	78.7	623.6	32.3	733.5	39.0	19.3	3.6	8.3	79.5	638.6	32.5	749.2	41.5	19.6	6.3	14.5	80.0
				60	686.7	33.2	799.7	41.8	20.7	1.7	3.9	81.3	728.5	33.9	843.7	47.1	21.5	3.6	8.3	82.5	749.1	34.2	865.3	50.1	21.9	6.3	14.5	83.1
				70	786.8	34.7	905.0	49.1	22.6	1.7	3.9	84.2	842.4	35.6	963.6	55.0	23.7	3.6	8.3	85.8	870.2	36.0	992.9	58.4	24.1	6.3	14.5	86.6
				80	892.3	36.4	1016.2	56.2	24.5	1.7	3.9	87.2																
	113	3.7	8.6	50	606.0	30.4	709.3	34.0	20.0	1.7	3.9	72.6																
				60	703.3	31.5	810.6	41.3	22.3	1.7	3.9	74.4	748.6	32.1	857.9	46.7	23.3	3.6	8.3	75.3	771.1	32.4	881.4	49.8	23.8	6.3	14.5	75.7
				70	807.4	32.9	919.3	48.5	24.6	1.7	3.9	76.4	868.4	33.7	982.9	54.6	25.8	3.6	8.3	77.5	899.2	34.1	1015.1	58.0	26.4	6.3	14.5	78.1
				80	917.6	34.3	1034.3	55.5	26.7	1.7	3.9	78.5																
75	75	1.7	4.0	30									409.1	34.5	526.6	22.8	11.8	3.6	8.3	89.0	415.4	34.6	533.3	24.5	12.0	6.3	14.5	89.2
				40	470.9	35.5	591.7	27.6	13.3	1.7	3.9	90.8	489.6	35.8	611.4	31.4	13.7	3.6	8.3	91.3	498.6	35.9	620.9	33.4	13.9	6.3	14.5	91.6
				50	553.2	36.8	678.3	35.4	15.0	1.7	3.9	93.1	579.3	37.2	705.8	39.8	15.6	3.6	8.3	93.9	592.0	37.4	719.2	42.2	15.8	6.3	14.5	94.3
				60	642.4	38.2	772.3	43.0	16.8	1.7	3.9	95.7	678.2	38.7	810.0	48.0	17.5	3.6	8.3	96.7	695.7	39.0	828.5	50.8	17.8	6.3	14.5	97.2
				70	738.1	39.7	873.2	50.4	18.6	1.7	3.9	98.4	785.9	40.5	923.7	56.0	19.4	3.6	8.3	99.8	809.6	40.9	948.7	59.2	19.8	6.3	14.5	100.5
				80	839.3	41.4	980.1	57.6	20.3	1.7	3.9	101.4																
	113	3.7	8.6	30									418.3	33.1	531.1	22.7	12.6	3.6	8.3	84.4	425.1	33.2	538.1	24.4	12.8	6.3	14.5	84.5
				40	481.9	33.9	597.3	27.3	14.2	1.7	3.9	85.6	502.0	34.2	618.3	31.2	14.7	3.6	8.3	86.0	511.8	34.3	628.4	33.2	14.9	6.3	14.5	86.2
				50	567.4	34.9	686.3	35.0	16.2	1.7	3.9	87.2	595.8	35.3	715.9	39.5	16.9	3.6	8.3	87.8	609.6	35.5	730.3	41.9	17.2	6.3	14.5	88.0
				60	660.5	36.1	783.2	42.5	18.3	1.7	3.9	89.0	699.7	36.6	824.1	47.6	19.1	3.6	8.3	89.7	719.0	36.8	844.3	50.4	19.5	6.3	14.5	90.1
				70	760.6	37.3	887.6	49.8	20.4	1.7	3.9	90.9	813.5	38.0	942.9	55.6	21.4	3.6	8.3	91.9	840.0	38.3	970.5	58.8	21.9	6.3	14.5	92.4
				80	866.8	38.7	998.5	56.9	22.4	1.7	3.9	92.9																
	150	6.5	15.1	30									422.9	32.5	533.3	22.6	13.0	3.6	8.3	82.1	429.9	32.5	540.6	24.3	13.2	6.3	14.5	82.2
				40	487.4	33.1	600.2	27.1	14.7	1.7	3.9	83.0	508.2	33.4	621.8	31.1	15.2	3.6	8.3	83.3	518.3	33.5	632.3	33.2	15.5	6.3	14.5	83.4
				50	574.4	34.1	690.4	34.8	16.9	1.7	3.9	84.2	604.0	34.4	721.0	39.3	17.6	3.6	8.3	84.6	618.4	34.5	735.9	41.8	17.9	6.3	14.5	84.8
				60	669.4	35.1	788.8	42.2	19.1	1.7	3.9	85.6	710.4	35.5	831.3	47.4	20.0	3.6	8.3	86.1	730.7	35.7	852.4	50.3	20.4	6.3	14.5	86.4
				70	771.7	36.2	894.8	49.5	21.3	1.7	3.9	87.0	827.3	36.8	952.6	55.3	22.5	3.6	8.3	87.8	855.3	37.2	981.7	58.6	23.0	6.3	14.5	88.2
				80	880.3	37.4	1007.8	56.5	23.5	1.7	3.9	88.5																
90	75	1.7	4.0	30	361.9	40.2	498.9	20.5	9.0	1.7	3.9	103.3	372.6	40.5	510.4	23.5	9.2	3.6	8.3	103.7	377.8	40.6	515.9	25.0	9.3	6.3	14.5	103.8
				40	431.9	41.5	573.4	28.6	10.4	1.7	3.9	105.4	447.4	41.8	589.8	32.1	10.7	3.6	8.3	105.8	454.8	42.0	597.7	34.0	10.8	6.3	14.5	106.0
				50	509.2	42.9	655.3	36.5	11.9	1.7	3.9	107.6	533.6	43.3	681.1	40.6	12.3	3.6	8.3	108.3	544.2	43.5	692.4	42.8	12.5	6.3	14.5	108.6
				60	596.3	44.4	747.5	44.2	13.4	1.7	3.9	110.1	626.4	44.9	779.4	48.9	13.9	3.6	8.3	111.0	641.1	45.2	794.9	51.5	14.2	6.3	14.5	111.4
				70	687.3	46.0	843.9	51.7	14.9	1.7	3.9	112.8	727.7	46.7	886.8	57.1	15.6	3.6	8.3	114.0	747.6	47.1	907.9	60.0	15.9	6.3	14.5	114.5
				80	771.4	47.5	933.1	59.4	16.2	1.7	3.9	115.2																
	113	3.7	8.6	30	370.8	38.6	502.3	20.2	9.6	1.7	3.9	98.9	382.4	38.8	514.5	23.3	9.9	3.6	8.3	99.2	387.9	38.9	520.3	24.9	10.0	6.3	14.5	99.3
				40	443.7	39.7	578.7	28.3	11.2	1.7	3.9	100.3	460.4	39.9	596.2	31.9	11.5	3.6	8.3	100.6	468.5	40.0	604.7	33.8	11.7	6.3	14.5	100.8
				50	524.4	40.7	663.0	36.1	12.9	1.7	3.9	101.9	548.2	41.0	687.8	40.3	13.4	3.6	8.3	102.3	559.7	41.2	699.9	42.6	13.6	6.3	14.5	102.5
				60	612.7	41.8	755.2	43.7	14.6	1.7	3.9	103.5	645.8	42.3	789.7	48.6	15.3	3.6	8.3	104.2	662.0	42.5	806.6	51.2	15.6	6.3	14.5	104.5
				70	708.2	43.1	854.8	51.2	16.4	1.7	3.9	105.4	753.1	43.7	901.8	56.6	17.3	3.6	8.3	106.2	775.4	44.0	925.0	59.7	17.6	6.3	14.5	106.7
				80	805.0	44.3	956.1	58.5	18.2	1.7	3.9	107.2																
	150	6.5	15.1	30	375.2	37.9	504.1	20.1	9.9	1.7	3.9	96.7	387.2	38.0	516.6	23.2	10.2	3.6	8.3	96.9	393.0	38.1	522.6	24.8	10.3	6.3	14.5	97.0
				40	449.5	38.7	581.4	28.1	11.6	1.7	3.9	97.8	466.9	38.9	599.5	31.8	12.0	3.6	8.3	98.0	475.4	39.0	608.3	33.7	12.2	6.3	14.5	98.1
				50	531.9	39.6	666.9	35.9	13.4	1.7	3.9	98.9	556.8	39.9	692.7	40.2	13.9	3.6	8.3	99.3	568.9	40.1	705.3	42.5	14.2	6.3	14.5	99.5
				60	622.3	40.6	760.6	43.5	15.3	1.7	3.9	100.2	657.1	41.0	796.7	48.4	16.0	3.6	8.3	100.7	674.2	41.2	814.4	51.0	16.4	6.3	14.5	101.0
				70	720.1	41.7	862.1	50.8	17.3	1.7	3.9	101.6	767.6	42.2	911.4	56.4	18.2	3.6	8.3	102.3	791.3	42.5	935.9	59.5	18.6	6.3	14.5	102.6
				80	824.5	42.9	970.5	58.0	19.2	1.7	3.9	103.1																
105	75	1.7	4.0	30	327.0	47.4	488.4	21.4	6.9	1.7	3.9	118.1	335.6	47.6	497.8	24.1	7.0	3.6	8.3	118.4	339.7	47.7	502.3	25.5	7.1	6.3	14.5	118.5
				40	391.8	48.9	558.4	29.7	8.0	1.7	3.9	120.0	404.3	49.2	571.8	32.9	8.2	3.6	8.3	120.4	410.3	49.3	578.2	34.6	8.3	6.3	14.5	120.6
				50	463.8	50.4	635.5	37.7	9.2	1.7	3.9	122.1	481.4	50.8	654.3	41.5	9.5	3.6	8.3	122.7	489.8	50.9	663.3	43.5	9.6	6.3	14.5	122.9
				60	542.5	52.0	719.7	45.6	10.4	1.7	3.9	124.4	566.8	52.5	745.6	50.0	10.8	3.6	8.3	125.2	578.5	52.7	758.1	52.3	11.0	6.3	14.5	125.5
				70	627.6	53.7	810.4	53.3	11.7	1.7	3.9	126.9	660.2	54.3	845.4	58.3	12.1	3.6	8.3	127.9	676.1	54.7	862.3	61.0	12.4	6.3	14.5	128.4
				80	689.3	54.9	876.5	61.6	12.5	1.7	3.9	128.8																
	113	3.7	8.6	30	336.4	45.5	491.4	21.1	7.4	1.7	3.9	113.8	345.8	45.7	501.3	23.9	7.6	3.6	8.3	114.0	350.3	45.8	506.1	25.4	7.7	6.3	14.5	114.1
				40	404.3	46.7	563.2	29.3	8.7	1.7	3.9	115.1	418.0	46.9	577.6	32.6	8.9	3.6	8.3	115.4	424.6	47.0	584.6	34.4	9.0	6.3	14.5	115.5
				50	479.9	47.8	642.8	37.3	10.0	1.7	3.9	116.5	499.5	48.1	663.3	41.2	10.4	3.6	8.3	116.9	508.9	48.2	673.2	43.3	10.6	6.3	14.5	117.1
				60	563.2	49.0	730.1	45.1	11.5	1.7	3.9	118.1	590.5	49.4	758.7	49.5	12.0	3.6	8.3	118.7	603.8	49.6	772.7	52.0	12.2	6.3	14.5	118.9
				70	653.5	50.3	824.7	52.6	13.0	1.7	3.9	119.9	690.9	50.8	863.9	57.7	13.6	3.6	8.3	120.6	709.2	51.1	883.1	60.6	13.9	6.3	14.5	121.0
				80	727.9	51.3	902.7	60.6	14.2	1.7	3.9	121.3																
	150	6.5	15.1	30	341.0	44.6	492.9	21.0	7.6	1.7	3.9	111.6	350.8	44.7	503.2	23.8	7.8	3.6	8.3	111.8	355.5	44.8	508.1	25.3	7.9	6.3	14.5	111.8
				40	410.5	45.6	565.7	29.2	9.0	1.7	3.9	112.6	424.8	45.8	580.6	32.5	9.3	3.6	8.3	112.8	431.7	45.9	587.9	34.3	9.4	6.3	14.5	112.9
				50	487.9	46.6	646.5	37.1	10.5	1.7	3.9	113.7	508.5	46.8	667.9	41.0	10.9	3.6	8.3	114.0	518.5	46.9	678.3	43.1	11.1	6.3	14.5	114.1
				60	573.4	47.6	735.3	44.8	12.1	1.7	3.9	114.9	602.3	47.9	765.4	49.3	12.6	3.6	8.3	115.3	616.4	48.1	780.1	51.8	12.8	6.3	14.5	115.5
				70	666.3	48.6	831.9	52.3	13.7	1.7	3.9	116.2	690.9	50.8	863.9	57.7	13.6	3.6	8.3	120.6	725.7	49.3	893.7	60.3	14.7	6.3	14.5	117.1
				80	747.5	49.6	916.3	60.1	15.1	1.7	3.9	117.4																
120	75	1.7	4.0	30	287.0	55.9	477.4	22.4	5.1	1.7	3.9	132.9	293.5	56.1	484.6	24.8	5.2	3.6	8.3	133.1	296.6	56.2	488.0	26.1	5.3	6.3	14.5	133.2
				40	345.4	57.6	541.7	30.9	6.0	1.7	3.9	134.6	354.8	57.9	552.0	33.8	6.1	3.6	8.3	134.9	359.3	58.0	556.9	35.3	6.2	6.3	14.5	135.1
				50	410.5	59.3	612.6	39.1	6.9	1.7	3.9	136.6	423.8	59.7	627.1	42.5	7.1	3.6	8.3	137.0	430.2	59.8	634.0	44.3	7.2	6.3	14.5	137.2
				60	482.0	61.1	690.1	47.2	7.9	1.7	3.9	138.7	500.4	61.5	710.0	51.1	8.1	3.6	8.3	139.3	509.2	61.7	719.5	53.2	8.2	6.3	14.5	139.5
				70	559.3	62.9	773.6	55.1	8.9	1.7	3.9	141.0																
	113	3.7	8.6	30	297.1	53.7	480.0	22.2	5.5	1.7	3.9	128.6	304.3	53.9	487.8	24.7	5.6	3.6	8.3	128.8	307.7	53.9	491.5	25.9	5.7	6.3	14.5	128.8
				40	358.9	55.0	546.4	30.5	6.5	1.7	3.9	129.8	369.4	55.3	557.7	33.5	6.7	3.6	8.3	130.0	374.5	55.4	563.1	35.1	6.8	6.3	14.5	130.1
				50	428.1	56.3	620.1	38.7	7.6	1.7	3.9	131.2	443.2	56.6	636.1	42.2	7.8	3.6	8.3	131.5	450.5	56.7	643.8	44.0	7.9	6.3	14.5	131.6
				60	504.7	57.6	701.1	46.6	8.8	1.7	3.9	132.7	526.0	58.0	723.6	50.7	9.1	3.6	8.3	133.1	536.2	58.2	734.4	52.9	9.2	6.3	14.5	133.3
				70	588.2	59.0	789.2	54.3	10.0	1.7	3.9	134.3	617.4	59.5	820.0	59.0	10.4	3.6	8.3	134.9	630.7	59.7	834.0	61.6	10.6	6.3	14.5	135.1
	150	6.5	15.1	30	302.1	52.6	481.3	22.0	5.7	1.7	3.9	126.5	309.6	52.8	489.4	24.6	5.9	3.6	8.3	126.6	313.3	52.8	493.3	25.9	5.9	6.3	14.5	126.7
				40	365.5	53.8	548.7	30.4	6.8	1.7	3.9	127.4	376.6	54.0	560.5	33.4	7.0	3.6	8.3	127.6	382.0	54.1	566.1	35.0	7.1	6.3	14.5	127.6
				50	436.8	54.9	623.7	38.4	8.0	1.7	3.9	128.4	452.9	55.1	640.6	42.0	8.2	3.6	8.3	128.7	460.6	55.2	648.8	43.9	8.3	6.3	14.5	128.8
				60	515.8	56.0	706.5	46.3	9.2	1.7	3.9	129.6	538.6	56.3	730.3	50.5	9.6	3.6	8.3	129.9	549.7	56.4	741.9	52.7	9.7	6.3	14.5	130.1
				70	602.3	57.1	796.8	54.0	10.6	1.7	3.9	130.8	617.4	59.5	820.0	59.0	10.4	3.6	8.3	134.9	649.3	57.7	845.8	61.3	11.3	6.3	14.5	131.5

Table B.11 Continued - Submittal data for ClimateMaster TMW600 Large Series (60Hz I-P, HFC-410A) for a range of operating temperatures in heating mode (ClimateMaster, 2015; 2016).

Source				LOAD																								
EWT °F	Flow			EWT °F	Flow 75 GPM							SLWT °F	Flow 113 GPM							SLWT °F	Flow 150 GPM							SLWT °F
	GPM	WPD			TC	kW	HE	LLWT	COP	WPD			TC	kW	HE	LLWT	COP	WPD			TC	kW	HE	LLWT	COP	GPM		
		PSI	FT							PSI	FT							PSI	FT							PSI	FT	
30	75	1.7	3.9	100	492.4	44.89	339.5	113.2	3.2	1.7	4.0	21.1	495.5	43.09	348.7	108.9	3.4	3.7	8.6	20.8	497.1	42.21	353.3	106.7	3.5	6.5	15.1	20.7
	113	3.6	8.3	80	521.1	36.38	397.3	93.9	4.2	1.7	4.0	23.0	525.5	34.91	406.7	89.3	4.4	3.7	8.6	22.9	527.7	34.19	411.3	87.0	4.5	6.5	15.1	22.8
				100	502.5	45.10	348.9	113.5	3.3	1.7	4.0	23.9	506.2	43.26	358.9	109.0	3.4	3.7	8.6	23.7	508.1	42.36	363.9	106.8	3.5	6.5	15.1	23.6
				120	484.6	56.10	293.5	133.1	2.5	1.7	4.0	24.8	487.8	53.86	304.3	128.8	2.7	3.7	8.6	24.7	489.4	52.77	309.6	126.6	2.7	6.5	15.1	24.6
				130									479.1	60.11	274.3	138.6	2.3	3.7	8.6	25.2	480.7	58.91	280.0	136.5	2.4	6.5	15.1	25.1
	150	6.3	14.5	80	527.4	36.48	403.2	94.1	4.2	1.7	4.0	24.7	532.1	34.99	413.0	89.5	4.5	3.7	8.6	24.6	534.5	34.26	417.9	87.1	4.6	6.5	15.1	24.5
				100	507.3	45.20	353.4	113.6	3.3	1.7	4.0	25.3	511.4	43.34	363.8	109.1	3.5	3.7	8.6	25.2	513.5	42.43	369.0	106.9	3.5	6.5	15.1	25.1
				120	488.0	56.20	296.6	133.2	2.5	1.7	4.0	26.1	491.5	53.94	307.7	128.8	2.7	3.7	8.6	25.9	493.3	52.84	313.3	126.7	2.7	6.5	15.1	25.9
				130									482.2	60.19	277.1	138.7	2.3	3.7	8.6	26.3	483.9	58.98	283.0	136.5	2.4	6.5	15.1	26.3
40	75	1.7	3.9	60	610.3	30.59	506.2	76.2	5.8	1.7	4.0	26.6																
				80	585.5	37.38	458.3	95.6	4.6	1.7	4.0	27.9	591.0	35.70	469.6	90.5	4.9	3.7	8.6	27.6	593.9	34.88	475.1	87.9	5.0	6.5	15.1	27.5
				100	564.0	46.30	406.3	115.2	3.6	1.7	4.0	29.3	569.0	44.19	418.5	110.2	3.8	3.7	8.6	29.0	571.5	43.16	424.6	107.7	3.9	6.5	15.1	28.8
				120	541.7	57.62	345.4	134.6	2.8	1.7	4.0	30.9	546.4	55.04	358.8	129.8	2.9	3.7	8.6	30.5	548.7	53.79	365.5	127.4	3.0	6.5	15.1	30.3
				130									534.9	61.46	325.4	139.7	2.6	3.7	8.6	31.4	537.3	60.08	332.6	137.3	2.6	6.5	15.1	31.2
	113	3.6	8.3	60	633.4	30.91	528.3	76.8	6.0	1.7	4.0	30.7																
				80	604.1	37.67	475.9	96.2	4.7	1.7	4.0	31.6	610.9	35.93	488.6	90.9	5.0	3.7	8.6	31.4	614.3	35.09	494.9	88.2	5.1	6.5	15.1	31.3
				100	578.4	46.58	419.8	115.6	3.6	1.7	4.0	32.6	584.5	44.41	433.3	110.5	3.9	3.7	8.6	32.4	587.6	43.35	440.0	107.9	4.0	6.5	15.1	32.3
				120	552.0	57.88	354.8	134.9	2.8	1.7	4.0	33.7	557.6	55.26	369.4	130.0	3.0	3.7	8.6	33.5	560.5	53.97	376.6	127.6	3.0	6.5	15.1	33.4
				130									544.1	61.66	334.0	139.8	2.6	3.7	8.6	34.1	547.0	60.26	341.7	137.4	2.7	6.5	15.1	34.0
	150	6.3	14.5	60	644.6	31.07	538.9	77.1	6.1	1.7	4.0	32.9																
				80	613.1	37.81	484.4	96.4	4.8	1.7	4.0	33.6	620.4	36.05	497.7	91.1	5.0	3.7	8.6	33.4	624.2	35.20	504.4	88.3	5.2	6.5	15.1	33.3
				100	585.4	46.71	426.3	115.7	3.7	1.7	4.0	34.4	592.0	44.51	440.4	110.6	3.9	3.7	8.6	34.2	595.3	43.44	447.4	108.0	4.0	6.5	15.1	34.1
				120	556.9	58.01	359.3	135.1	2.8	1.7	4.0	35.3	563.1	55.36	374.5	130.1	3.0	3.7	8.6	35.1	566.1	54.06	382.0	127.6	3.1	6.5	15.1	35.0
				130									548.5	61.76	338.0	139.9	2.6	3.7	8.6	35.5	551.6	60.35	346.0	137.5	2.7	6.5	15.1	35.4
50	75	1.7	3.9	60	701.3	31.84	592.9	78.7	6.5	1.7	4.0	34.3																
				80	670.6	38.68	538.9	98.0	5.1	1.7	4.0	35.7	678.5	36.73	553.5	92.1	5.4	3.7	8.6	35.3	682.5	35.79	560.7	89.1	5.6	6.5	15.1	35.2
				100	642.9	47.76	480.2	117.3	3.9	1.7	4.0	37.3	650.3	45.30	496.0	111.7	4.2	3.7	8.6	36.9	654.1	44.10	503.9	108.8	4.3	6.5	15.1	36.7
				120	612.6	59.33	410.4	136.6	3.0	1.7	4.0	39.1	620.0	56.34	428.1	131.2	3.2	3.7	8.6	38.7	623.7	54.89	436.7	128.4	3.3	6.5	15.1	38.4
				130									603.8	62.89	389.5	140.9	2.8	3.7	8.6	39.7	607.7	61.30	398.9	138.2	2.9	6.5	15.1	39.4
	113	3.6	8.3	60	733.5	32.29	623.6	79.5	6.7	1.7	4.0	39.0																
				80	696.6	39.08	563.6	98.7	5.2	1.7	4.0	40.0	706.5	37.06	580.4	92.6	5.6	3.7	8.6	39.8	711.5	36.08	588.7	89.5	5.8	6.5	15.1	39.6
				100	663.2	48.13	499.3	117.9	4.0	1.7	4.0	41.2	672.3	45.59	517.1	112.1	4.3	3.7	8.6	40.9	677.0	44.36	526.0	109.1	4.5	6.5	15.1	40.7
				120	627.1	59.67	423.8	137.0	3.1	1.7	4.0	42.5	636.1	56.61	443.2	131.5	3.3	3.7	8.6	42.2	640.6	55.12	452.8	128.7	3.4	6.5	15.1	42.0
				130																	621.7	61.52	412.0	138.4	3.0	6.5	15.1	42.7
	150	6.3	14.5	60	749.2	32.52	638.6	80.0	6.8	1.7	4.0	41.5																
				80	709.2	39.27	575.5	99.0	5.3	1.7	4.0	42.4	720.1	37.22	593.4	92.9	5.7	3.7	8.6	42.1	725.7	36.23	602.4	89.7	5.9	6.5	15.1	42.0
				100	672.9	48.31	508.4	118.1	4.1	1.7	4.0	43.3	683.0	45.73	527.3	112.3	4.4	3.7	8.6	43.0	688.2	44.48	536.7	109.3	4.5	6.5	15.1	42.9
				120	634.0	59.83	430.2	137.2	3.1	1.7	4.0	44.3	643.8	56.74	450.5	131.6	3.3	3.7	8.6	44.0	648.8	55.23	460.6	128.8	3.4	6.5	15.1	43.9
				130																	628.3	61.62	418.4	138.5	3.0	6.5	15.1	44.5
60	75	1.7	3.9	60	799.7	33.22	686.7	81.3	7.1	1.7	4.0	41.8																
				80	763.0	40.09	626.6	100.5	5.6	1.7	4.0	43.4	773.9	37.85	645.1	93.8	6.0	3.7	8.6	42.9	779.4	36.78	654.2	90.4	6.2	6.5	15.1	42.6
				100	728.9	49.30	561.0	119.7	4.3	1.7	4.0	45.1	739.4	46.46	581.2	113.3	4.7	3.7	8.6	44.6	744.7	45.09	591.2	110.0	4.8	6.5	15.1	44.3
				120	690.0	61.07	481.9	138.7	3.3	1.7	4.0	47.2	701.0	57.64	504.6	132.7	3.6	3.7	8.6	46.6	706.4	55.97	515.8	129.6	3.7	6.5	15.1	46.3
				130																	685.5	62.46	472.7	139.3	3.2	6.5	15.1	47.4
	113	3.6	8.3	60	843.7	33.85	728.5	82.5	7.3	1.7	4.0	47.1	857.9	32.11	748.6	75.3	7.8	3.7	8.6	46.7								
				80	798.7	40.64	660.4	101.5	5.8	1.7	4.0	48.3	812.6	38.31	682.2	94.5	6.2	3.7	8.6	47.9	819.8	37.20	693.2	91.0	6.5	6.5	15.1	47.7
				100	756.9	49.80	587.3	120.4	4.5	1.7	4.0	49.6	770.1	46.86	610.5	113.9	4.8	3.7	8.6	49.2	776.9	45.44	622.2	110.5	5.0	6.5	15.1	49.0
				120	709.9	61.51	500.3	139.3	3.4	1.7	4.0	51.1	723.5	58.00	525.9	133.1	3.7	3.7	8.6	50.7	730.3	56.27	538.6	129.9	3.8	6.5	15.1	50.5
				130																	705.2	62.74	491.4	139.6	3.3	6.5	15.1	51.3
	150	6.3	14.5	60	865.3	34.17	749.1	83.1	7.4	1.7	4.0	50.1	881.4	32.40	771.1	75.7	8.0	3.7	8.6	49.8								
				80	816.1	40.91	676.8	101.9	5.8	1.7	4.0	51.0	831.7	38.54	700.5	94.9	6.3	3.7	8.6	50.7	839.7	37.41	712.4	91.3	6.6	6.5	15.1	50.5
				100	770.4	50.05	599.9	120.8	4.5	1.7	4.0	52.0	785.1	47.05	624.9	114.1	4.9	3.7	8.6	51.7	792.7	45.61	637.3	110.7	5.1	6.5	15.1	51.5
				120	719.5	61.73	509.1	139.5	3.4	1.7	4.0	53.2	734.4	58.16	536.2	133.3	3.7	3.7	8.6	52.9	741.8	56.41	549.6	130.1	3.9	6.5	15.1	52.7
				130																	714.7	62.87	500.4	139.7	3.3	6.5	15.1	53.3
70	75	1.7	3.9	60	905.0	34.74	786.8	84.2	7.6	1.7	4.0	49.1	919.3	32.86	807.5	76.4	8.2	3.7	8.6	48.5								
				80	862.4	41.63	720.6	103.2	6.1	1.7	4.0	50.8	876.7	39.08	743.7	95.7	6.6	3.7	8.6	50.2	884.0	37.88	755.1	91.9	6.8	6.5	15.1	49.9
				100	821.7	50.95	648.1	122.2	4.7	1.7	4.0	52.7	835.9	47.71	673.4	115.1	5.1	3.7	8.6	52.1	843.1	46.15	685.9	111.4	5.4	6.5	15.1	51.7
				120									789.1	58.99	588.1	134.3	3.9	3.7	8.6	54.3	796.7	57.08	602.2	130.8	4.1	6.5	15.1	54.0
	113	3.6	8.3	60	963.6	35.61	842.4	85.8	7.9	1.7	4.0	55.0	982.9	33.66	868.4	77.5	8.6	3.7	8.6	54.6								
				80	910.2	42.39	765.9	104.5	6.3	1.7	4.0	56.4	929.2	39.73	794.0	96.7	6.9	3.7	8.6	55.9	939.0	38.47	808.0	92.6	7.2	6.5	15.1	55.7
				100	859.4	51.64	683.5	123.3	4.9	1.7	4.0	57.9	877.8	48.26	713.5	115.8	5.3	3.7	8.6	57.3	887.3	46.63	728.5	112.0	5.6	6.5	15.1	57.1
				120									820.0	59.46	617.4	134.9	4.0	3.7	8.6	59.0	829.7	57.48	633.8	131.3	4.2	6.5	15.1	58.7
	150	6.3	14.5	60	992.9	36.05	870.2	86.6	8.1	1.7	4.0	58.4	1015.1	34.07	899.2	78.1	8.7	3.7	8.6	58.0								
				80	933.8	42.77	788.2	105.2	6.4	1.7	4.0	59.5	955.4	40.06	819.1	97.2	7.0	3.7	8.6	59.1	966.6	38.78	834.5	93.0	7.3	6.5	15.1	58.9
				100	877.7	51.97	700.6	123.8	4.9	1.7	4.0	60.7	898.5	48.53	733.2	116.2	5.4	3.7	8.6	60.2	909.2	46.87	749.5	112.3	5.7	6.5	15.1	60.0
				120									834.0	59.67	630.7	135.1	4.1	3.7	8.6	61.6	845.8	57.68	649.2	131.5	4.3	6.5	15.1	61.3

Table B.12 - GeoDistrict Energy model assumptions for equipment material selection and materials, and economic and climatic models.

C. GEODISTRICT ENERGY MODEL ASSUMPTIONS (EQUIPMENT, MATERIALS, ECONOMIC, AND CLIMATIC)		
Parameter	**Units**	**Description**
Pump Installation Cost - ($/kW)	150	(Reber, 2013)
Pipe Maintenance Cost - (% of pipe installation cost/yr)	0.02	2% of installation cost per year (Thorleikur, 2016)
Pumps Maintenance Cost - (% of pump installation cost/yr)	0.05	5% of installation cost per year (Thorleikur, 2016)
Utilization Pumping Power - (hours/year)	8760	(Thorleikur, 2016)
Discount Rate (dr) - (-)	0.05	(Beckers, 2016)
Inflation Rate (ir) - (-)	0.02	(Beckers, 2016)
Expected Lifetime (lt) of GeoDistrict System- (years)	20	(Beckers, 2016)
Mechanical Equipment Installation Cost - ($/ton)	2000	(Beckers, 2016)
Pumps, Piping & Installation Costs GHP - ($)	5000	(Beckers, 2016)
Fraction of year in Heating Mode (-)	0.71	From Climatic Model in Tab 3. Geothermal Model
Fraction of year in Cooling Mode (-)	0.29	From Climatic Model in Tab 3. Geothermal Model
Electricity Rate for Residential Consumption - ($/kWh)	0.18	(EIA, 2015)
Electricity Rate for Commercial Consumption - ($/kWh)	0.14	(EIA, 2015)
Commercial Incentive - (%)	10	(DSIRE, 2015)
Residential Incentive - (%)	30	(DSIRE, 2015)
Annual Maintenance Costs GHP - ($/year)	200	(Beckers, 2016)
Indoor Design Temperature (Ti) - (˚F)	70	(CSU, 1978; U.S. HUD, 1980)
Outdoor Heating Design Temperature (To,H) - (˚F)	-6	(CSU, 1978; U.S. HUD, 1980)
Outdoor Cooling Design Temperature (To,C) - (˚F)	85	(CSU, 1978; U.S. HUD, 1980)

Table B.12 Continued - GeoDistrict Energy model assumptions for equipment material selection and materials, and economic and climatic models.

C. GEODISTRICT ENERGY MODEL ASSUMPTIONS (EQUIPMENT, MATERIALS, ECONOMIC, AND CLIMATIC)		
Parameter	**Units**	**Description**
Typical Heating Degree Days (HDD) (Syracuse)	6803	(NYSERDA, 2017)
Typical Cooling Degree Days (CDD) (Syracuse)	550	(NYSERDA, 2017)
Commercial Electricity Rate of an Air Conditioner/ASHP (Cooling) - ($/MMBtu)	20	(IGSHPA, 2009)
Residential Electricity Rate of an Air Conditioner/ASHP (Cooling) - ($/MMBtu)	25	(IGSHPA, 2009)
Natural Gas Heating Rate for a Furnace or Boiler (Heating) - ($/MMBtu)	18.4	(IGSHPA, 2009)
Natural Gas Boiler Estimated Capital Cost - ($/Mbtu/hr)	35.0	(IGSHPA, 2009)
Density of water ($\rho_{fluid,DP}$) - (lb/ft^3)	62	
Density of water ($\rho_{fluid,DP}$) - (kg/m^3)	992.20	
Specific Heat Capacity of Water ($c_{p,DP}$)- (Btu/lb·°F)	1.01	
Supply Temperature ($T_{s,DHW}$) - (°F)	106.40	From Mechanical Equipment Assumptions in Tab 3. Geothermal
Supply Temperature ($T_{s,DHW}$) - (°C)	41.33	
Return Temperature ($T_{r,DHW}$) - (°F)	100	From Mechanical Equipment Assumptions in Tab 3. Geothermal
Return Temperature ($T_{r,DHW}$) - (°C)	38	
Average ground temperature ($T_{avg,DHT}$) of District Heating Trench - (°F)	48	Average annual surface temperature (Wilcox and Marion, 2008)
Average ground temperature ($T_{avg,DHT}$) of District Heating Trench - (°C)	9.0	
Fluid Viscosity (Water) in the distribution pipe (μ_{DP})- (cP)	0.68	
Gravity (g) - (m/s^2)	9.80	
Gravity (g) - (ft/s^2)	32.2	

Appendix B: Supporting Documentation for Chapter 6

Table B.12 Continued - GeoDistrict Energy model assumptions for equipment material selection and materials, and economic and climatic models.

C. GEODISTRICT ENERGY MODEL ASSUMPTIONS (EQUIPMENT, MATERIALS, ECONOMIC, AND CLIMATIC)		
Parameter	**Units**	**Description**
Pump Efficiency (η)	0.70	(Thorleikur, 2016)
Peak Boiler Efficiency (η_{NG})	0.85	(Reber, 2013)
Resistance Coefficient of Steel - (in)	0.00393701	(Thorleikur, 2016)
Specific Heat Capacity of water ($c_{p,DP}$)- (J/kg·K)	4200	
Average ground temperature of District Heating Trench - (°C)	9	Average annual surface temperature (Wilcox and Marion, 2008)
Total volumetric flow rate (V_{DP}) in the distribution pipe - (GPM)	1198	volumetric fluid flow rate Q = total heat load/(density of water*heat
Average Temperature of District Heating Water ($T_{avg,DHW}$) - (°F)	55	Average temperature of the water, Tm = (Ts + Tr)/(Tb)
Average Temperature of District Heating Water ($T_{avg,DHW}$) - (°C)	12.78	
Mass Flow rate of the district heating fluid ($\dot{m}_{DP}$) - (kg/s)	75.0	Mass flow rate = volumetric flow rate * density of water
Thermal Conductivity of Steel (K_{steel}) - (W/mK)	50	(Set Pipes, 2017)
Thermal Conductivity of PUR Insulation (K_{pur}) - (W/mK)	0.026	(Set Pipes, 2017)
Thermal Conductivity of PE Casing (K_{PE}) - (W/mK)	0.40	(Set Pipes, 2017)
Thermal Conductivity of Sand (K_{sand}) - (W/mK)	0.15	(Thorleikur, 2016)
Thermal Conductivity of Soil (K_{soil}) - (W/mK)	1.20	(Set Pipes, 2017)
Thickness of Sand (δ_{sand}) - (m)	0.15	(Thorleikur, 2016)
Thickness of Soil (δ_{soil}) - (m)	0.55	(Thorleikur, 2016)